Finite Element Flow Simulations of the EUROLIFT DLR-F11 High Lift Configuration

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Objectives

- Study grid convergence and Reynolds number effect
- Compare adaptive refinement to manual refinement

Outline

- Introduction to solver and adaptivity
- Results
  - Case 1
  - Case 2a and 2b
- Future work

Flow Solver

- PHASTA (Parallel Hierarchic Adaptive Stabilized Transient Analysis)
- SUPG with piecewise linear finite elements (has support for higher order elements)
- Can solve incompressible and compressible Navier-Stokes equations
- Turbulence models: RANS-SA, LES, DES, VMS
- Generalized-α implicit time integrator
- GMRES linear algebra solver
- Block diagonal pre-conditioner
- Highly scalable! Shown to scale up to 3M MPI processes for a 92 billion tetrahedral element mesh for a rudder geometry

Adaptivity

- Adaptation can be useful to automatically get required resolution in specific areas of interest.

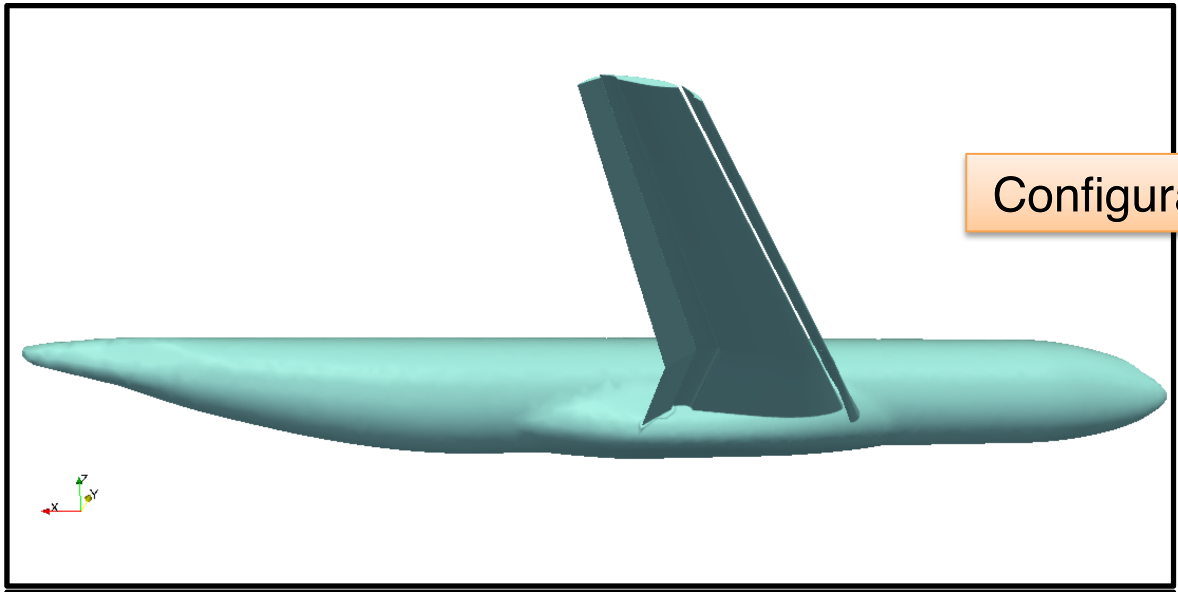
- Need to adapt inside the boundary layer as well -> need to alter the surface mesh AND improve the geometric approximation.

- Boundary layers adapted except in the thickness direction.

- A combined approach of PDE residuals for smallest mesh spacing and Hessians for relative scales and directions was used.

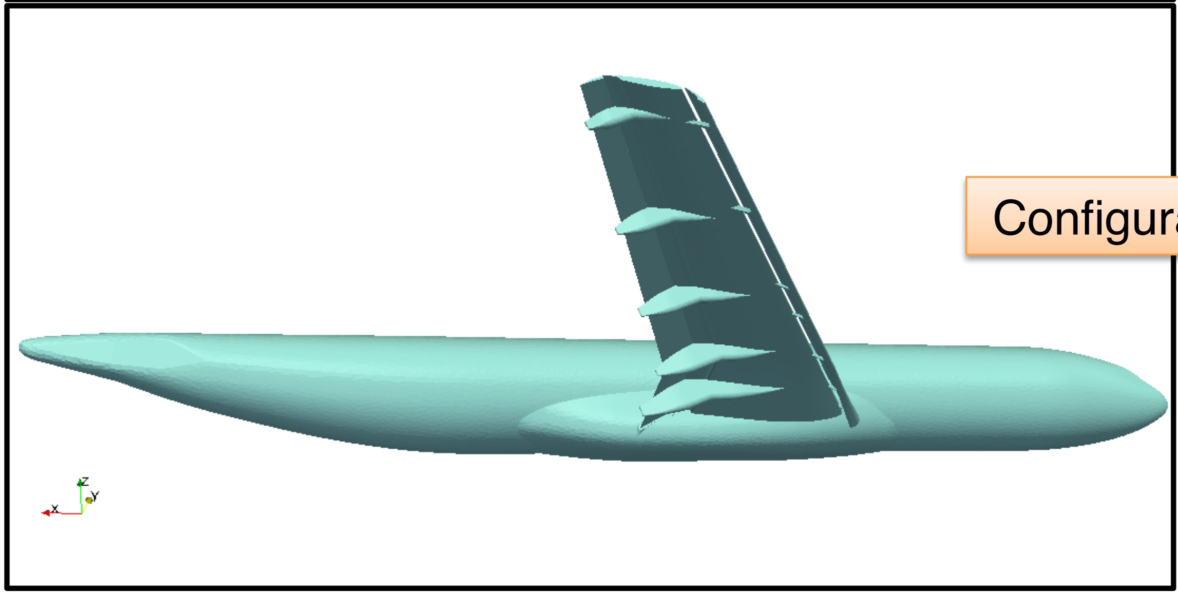
- Simmetrix Inc.'s boundary layer mesh adaptation software was used

Geometries



Configuration 2

Case 1



Configuration 4

Case 2a
Case 2b

Case 1: Description

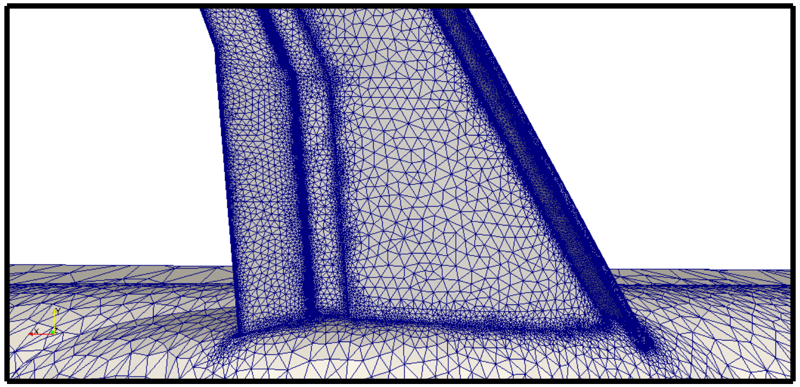
- Angles of attack: 7^o and 16^o

- Meshes:
  - Created in-house using gridding guidelines given online
  - Unstructured, with mixed element boundary layers
  - Created using MeshSim software by Simmetrix Inc.

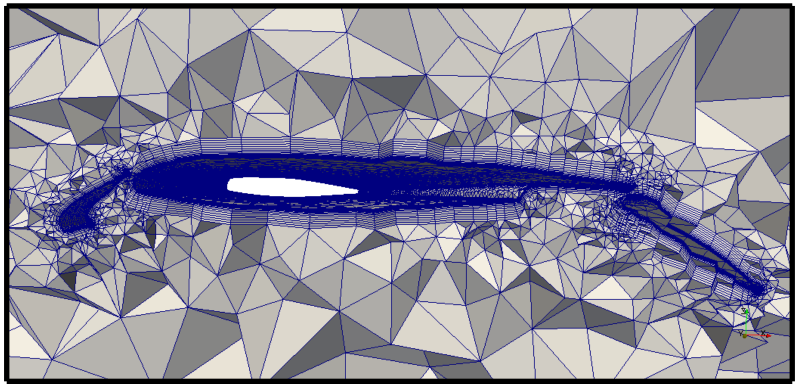
- Mesh statistics:

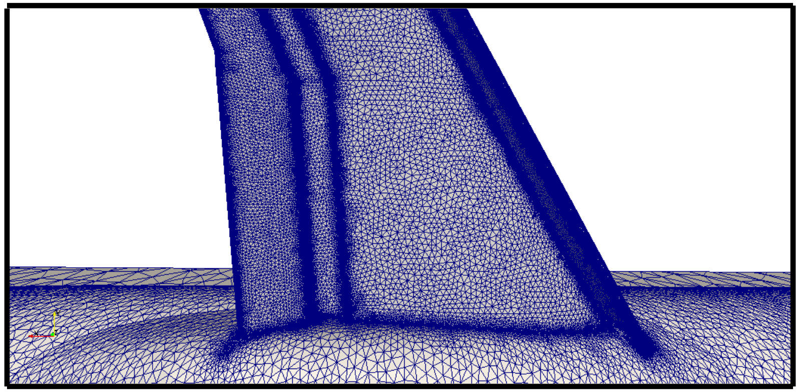
Meshes	# elements	# nodes	First cell height (m)
Coarse	32.2M	13.5M	5.5e-7
Medium	91.5M	37.3M	3.7e-7
Fine	287.9M	112.9M	2.4e-7

Case 1: Meshes



Coarse





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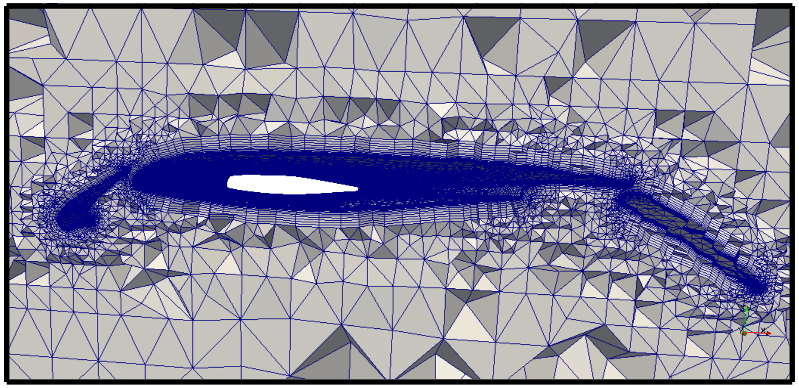
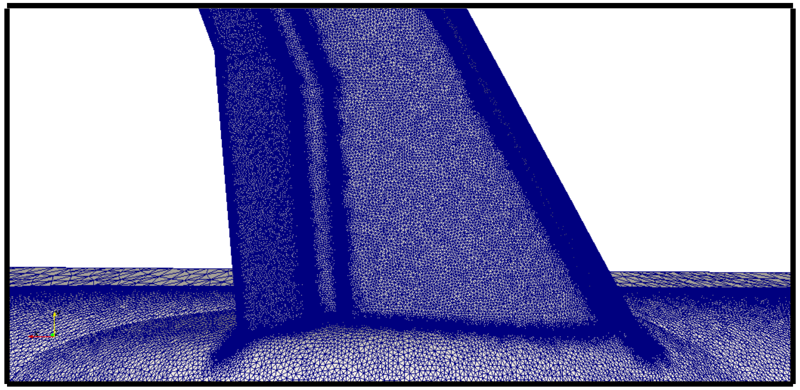
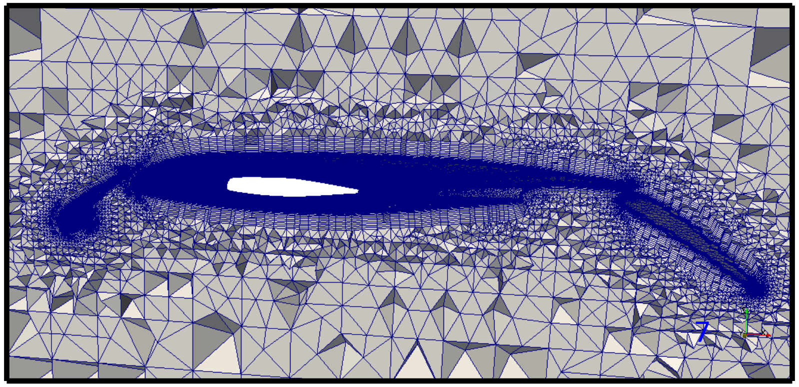
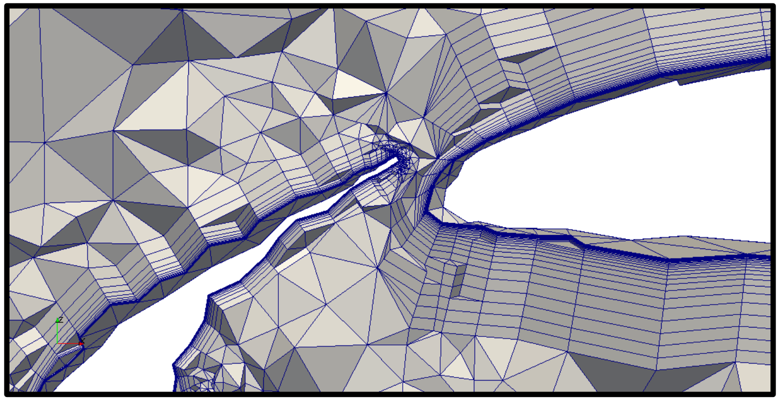




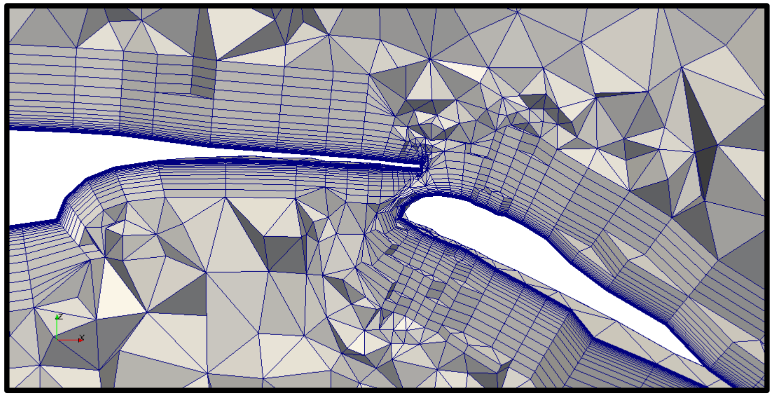
Fine

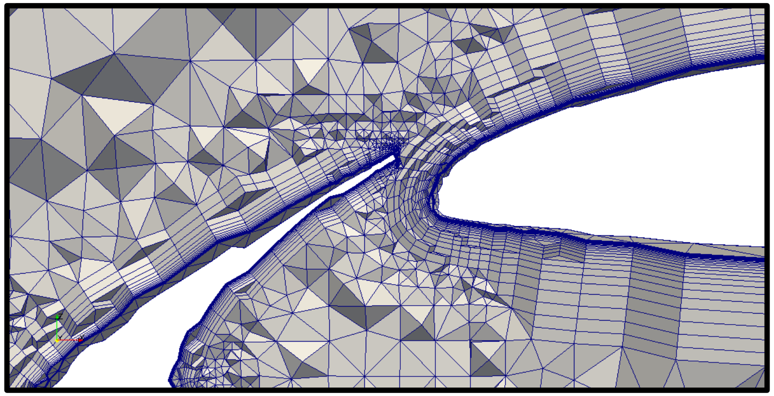


Case 1: Meshes

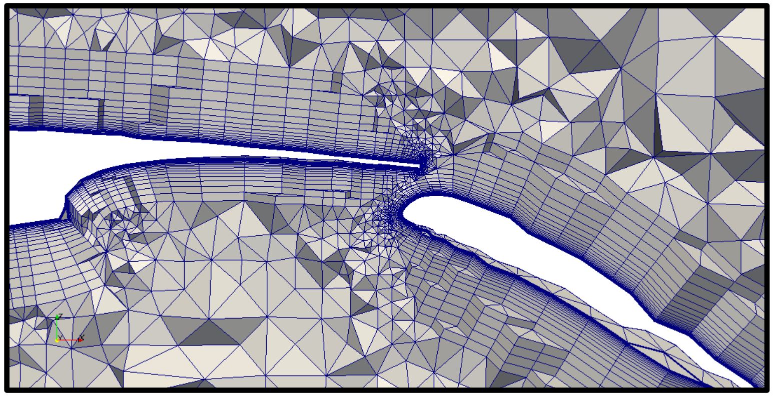


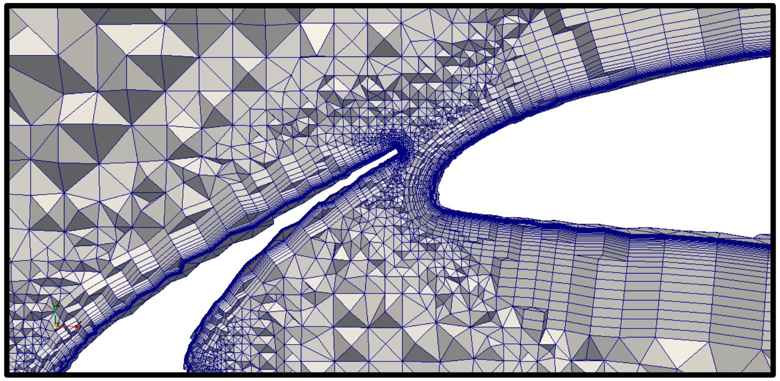
Coarse



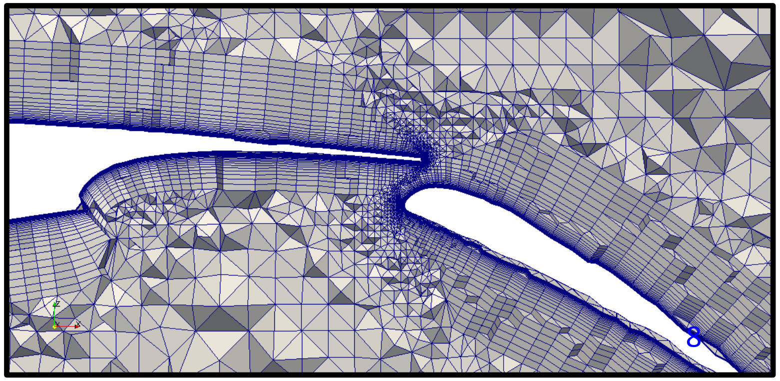


Medium





Fine



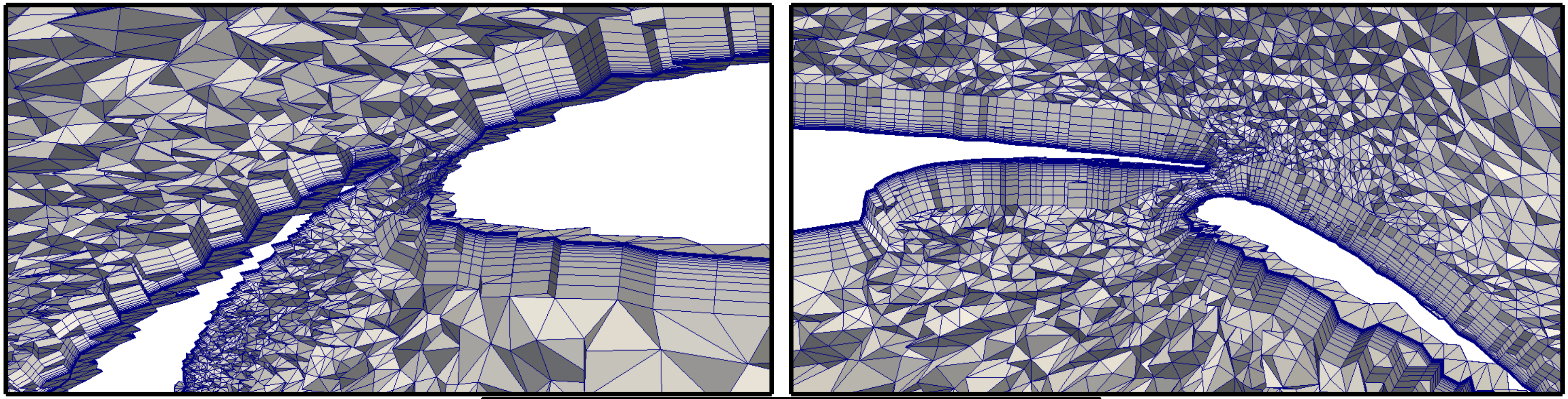
Case 1: Adaptivity

- One adaptivity pass was achieved on an extra coarse mesh to get comparable mesh to the coarse mesh

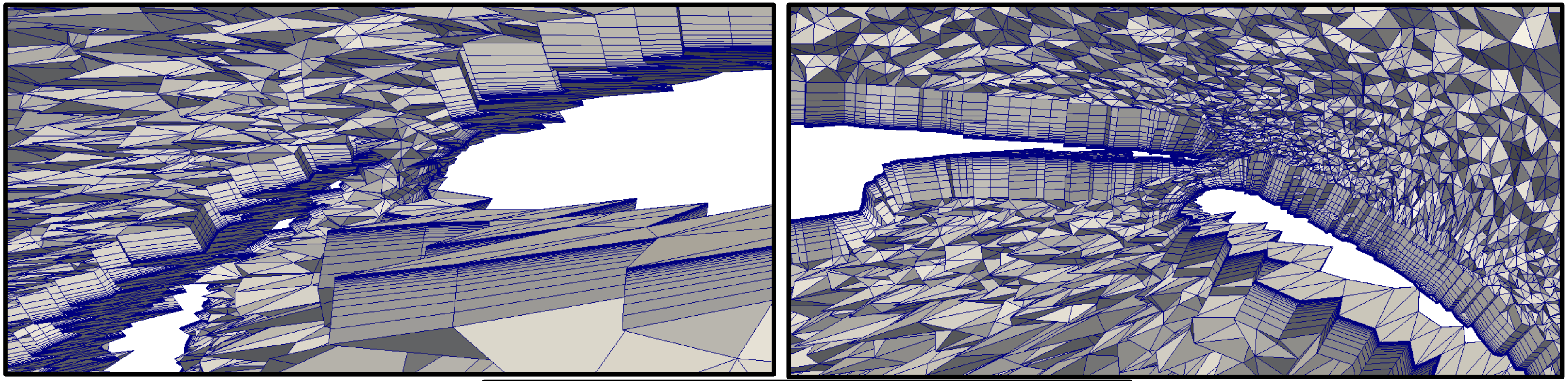
Mesh	# elements	# nodes	First cell height (m)
Adapted (7^o)	40.7M	14.1M	5.5e-7
Adapted (16^o)	35.1M	12.0M	5.5e-7

- Need to perform parallel adaptation further since the problem size is high -> not done in this study.

Case 1: Meshes



Zooms of the adapted mesh (7^o)



Zooms of the adapted mesh (16^o)

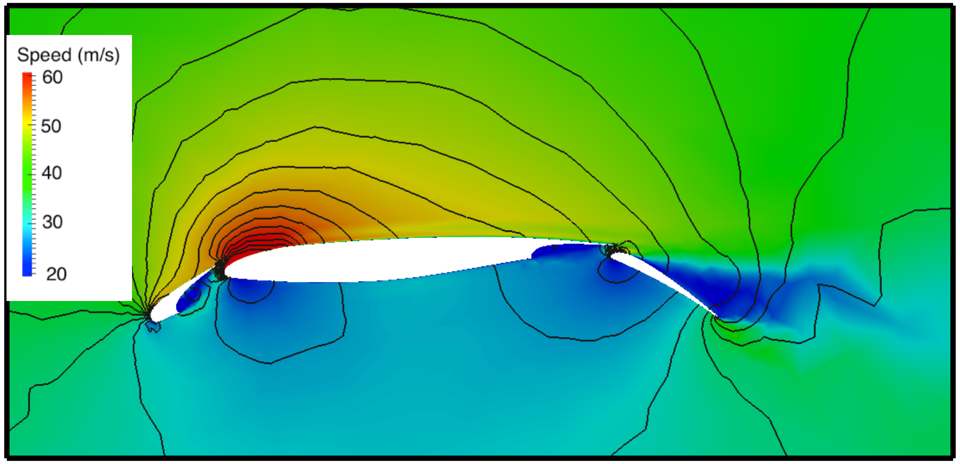
Case 1: Computational Details

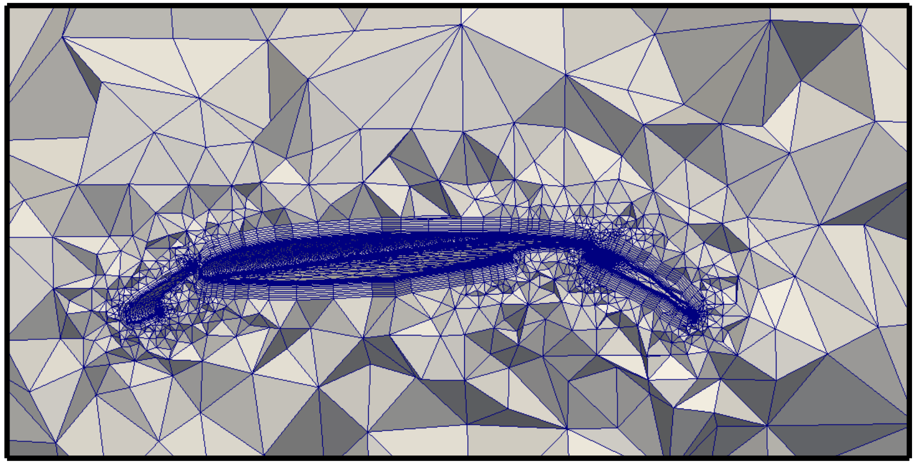
- Turbulence model: RANS Spalart-Allmaras
- Solved as time accurate
- Simulations performed on Janus supercomputer (UC Boulder) an Mira BG/Q (ANL)

Mesh	# cores	# elements/core
Coarse	1.8k	17930
Medium	32k	2790
Fine	64k	4390
Adapted	3.6k	10100

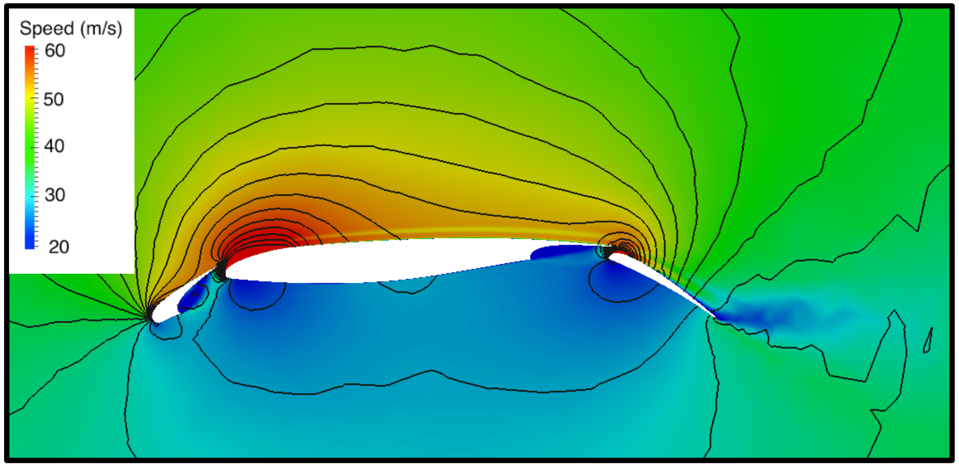
Computational details for AoA = 7^o

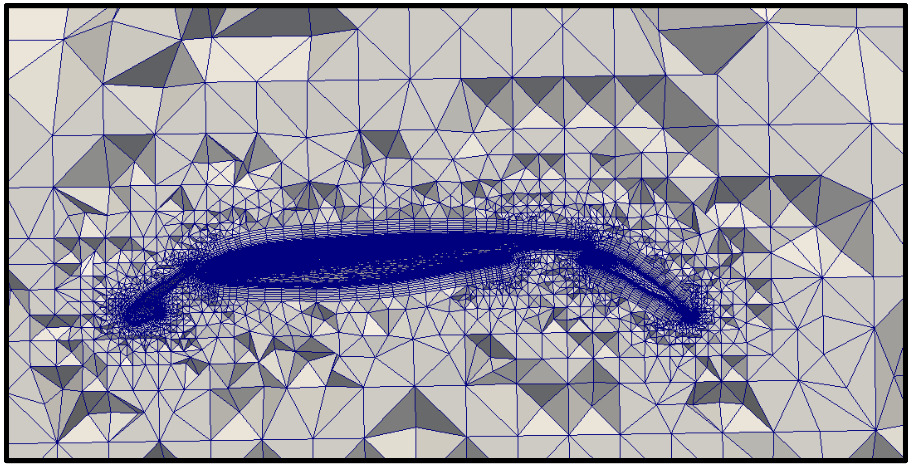
Case 1: Speed and Meshes





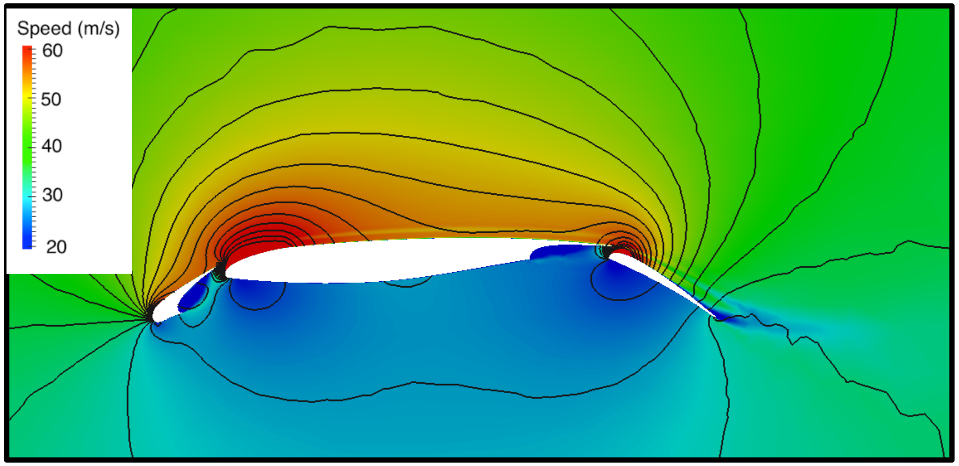
Coarse mesh

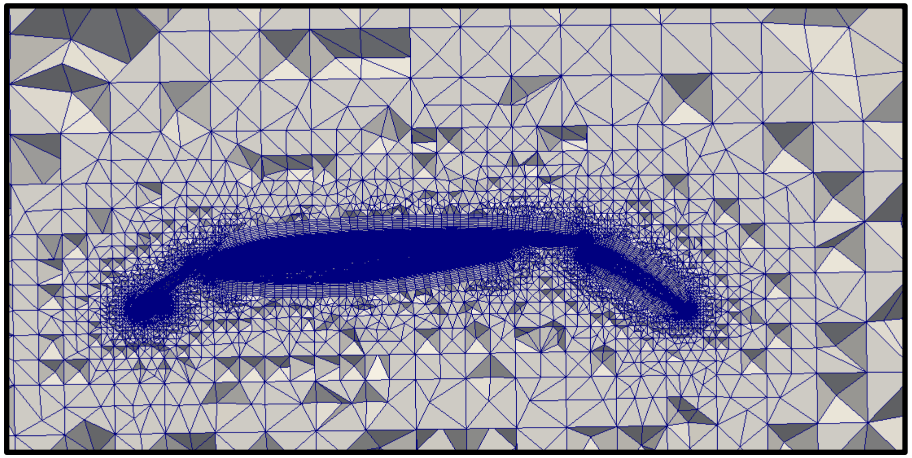




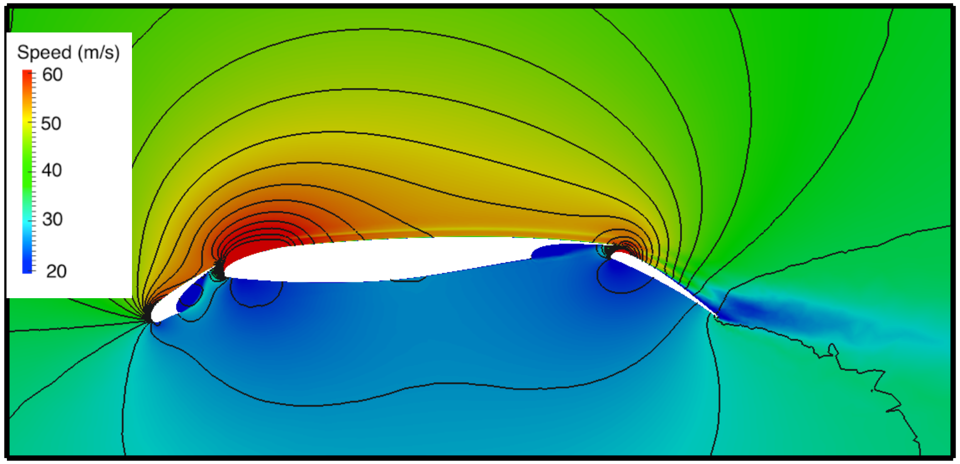
Medium mesh

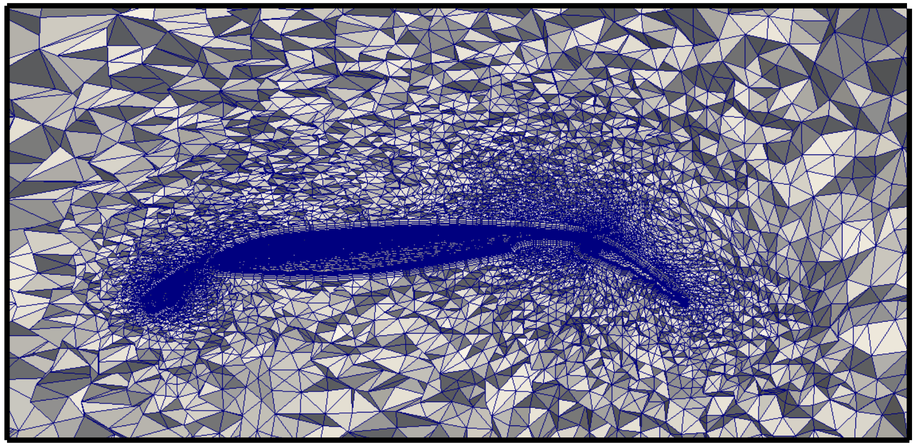
Case 1: Speed and Meshes





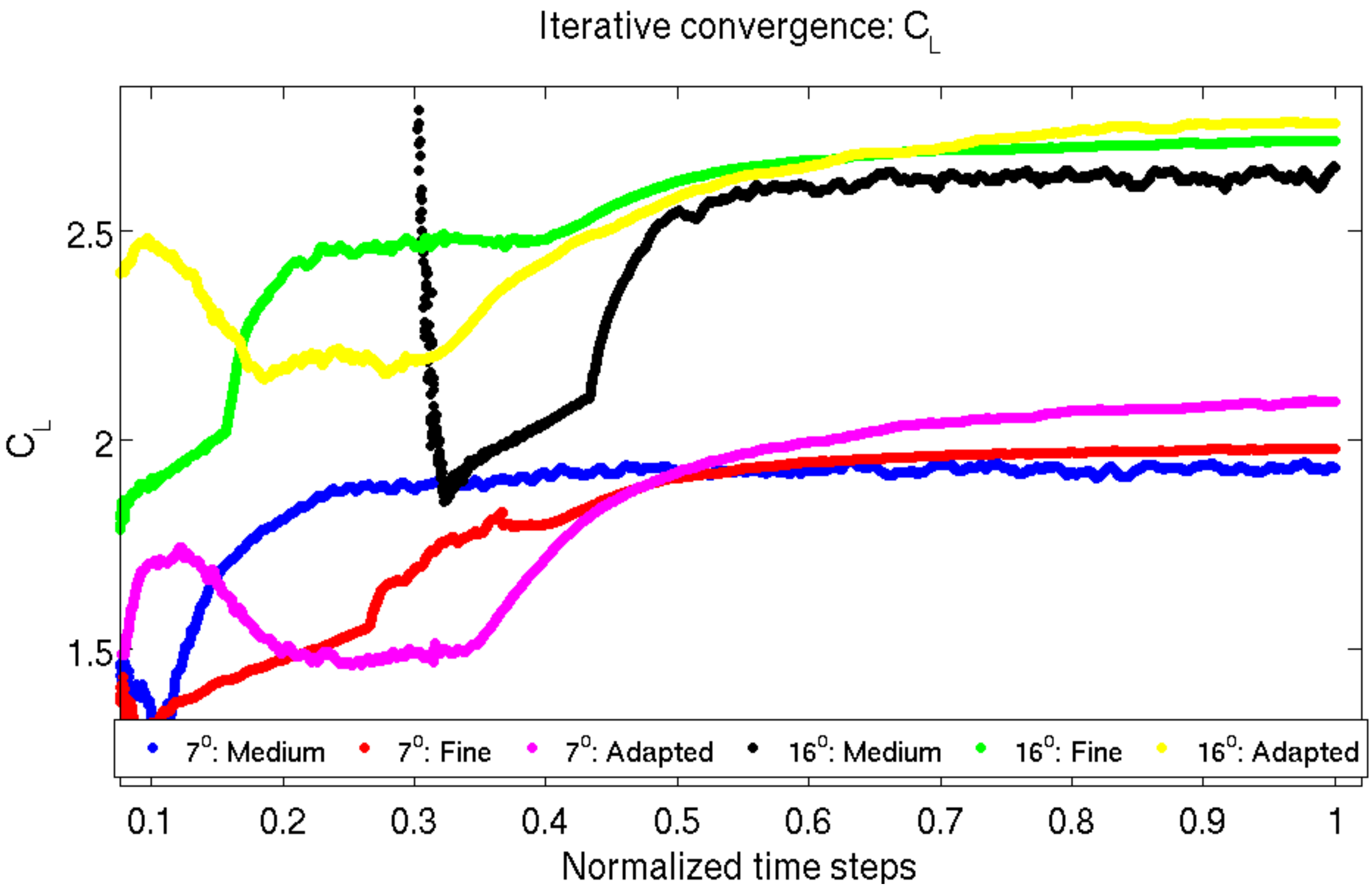
Fine mesh



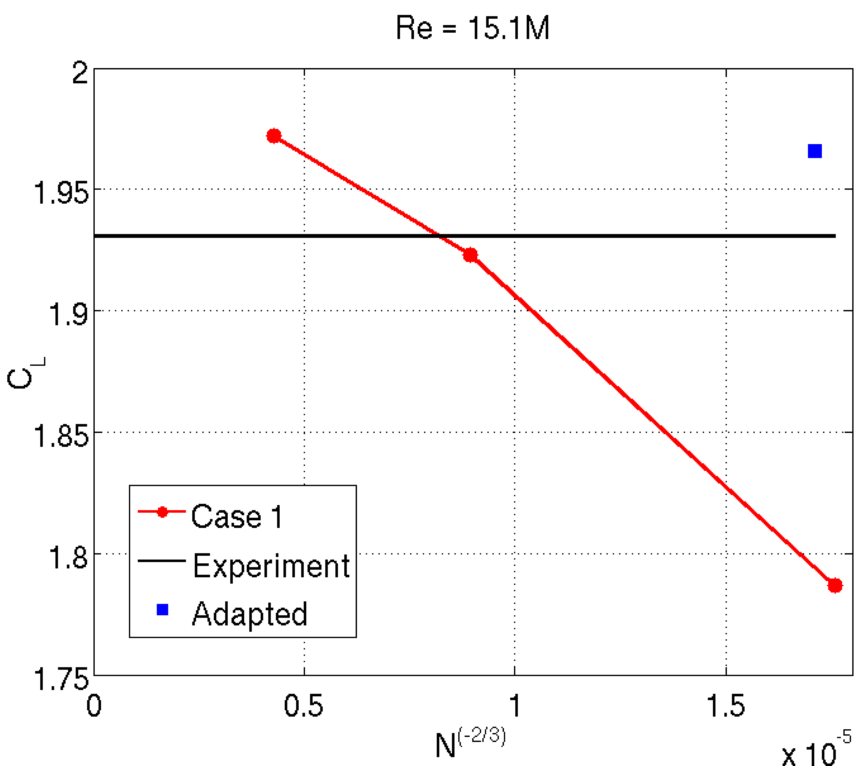


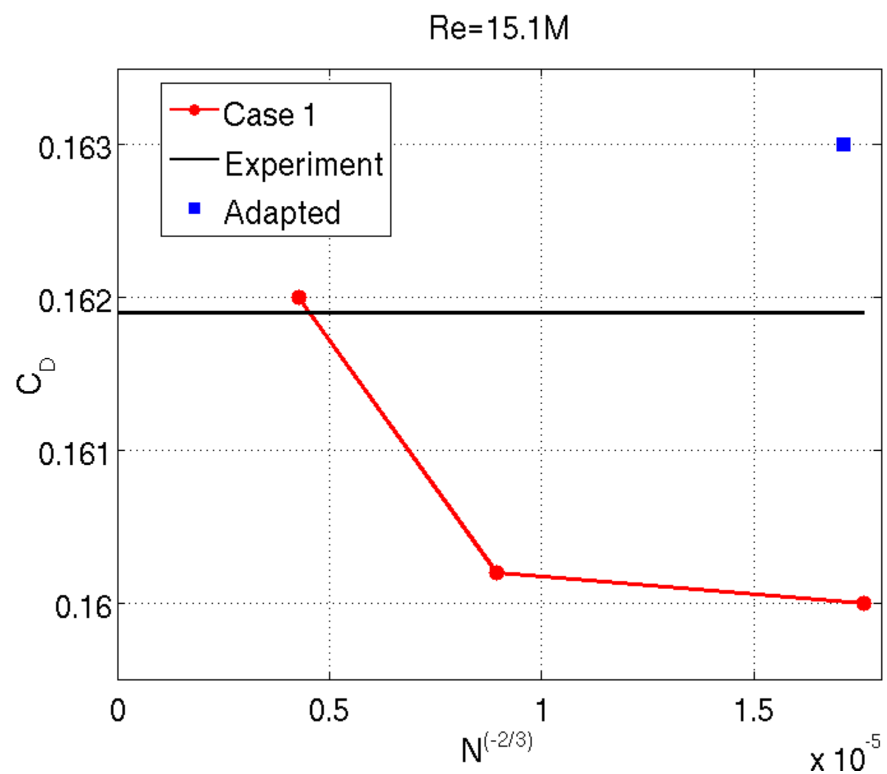
Adapted mesh

Case 1: Iterative Convergence



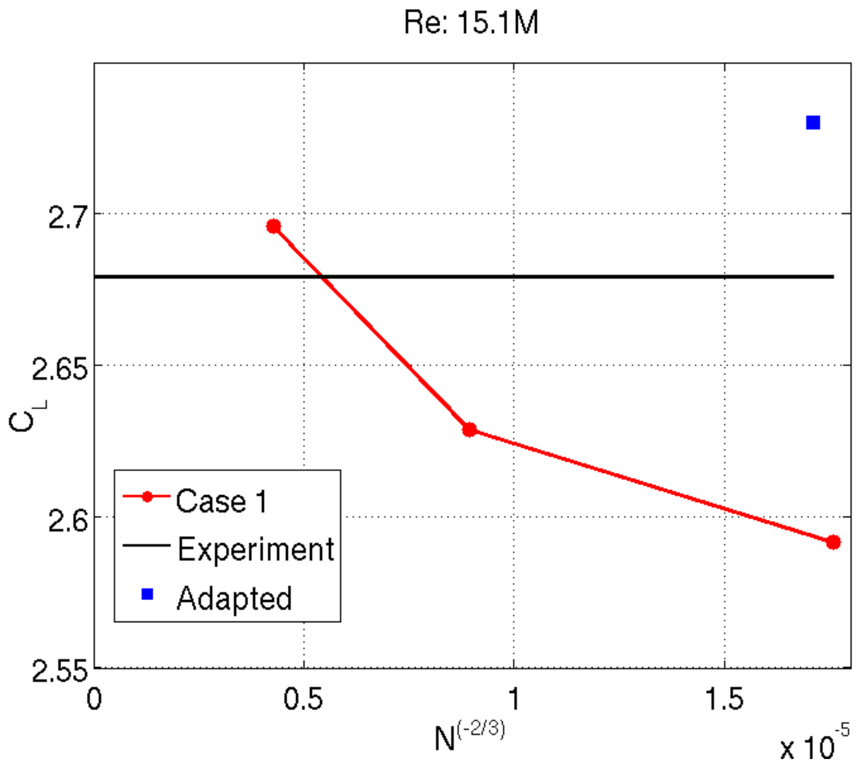
Case 1: Grid Convergence

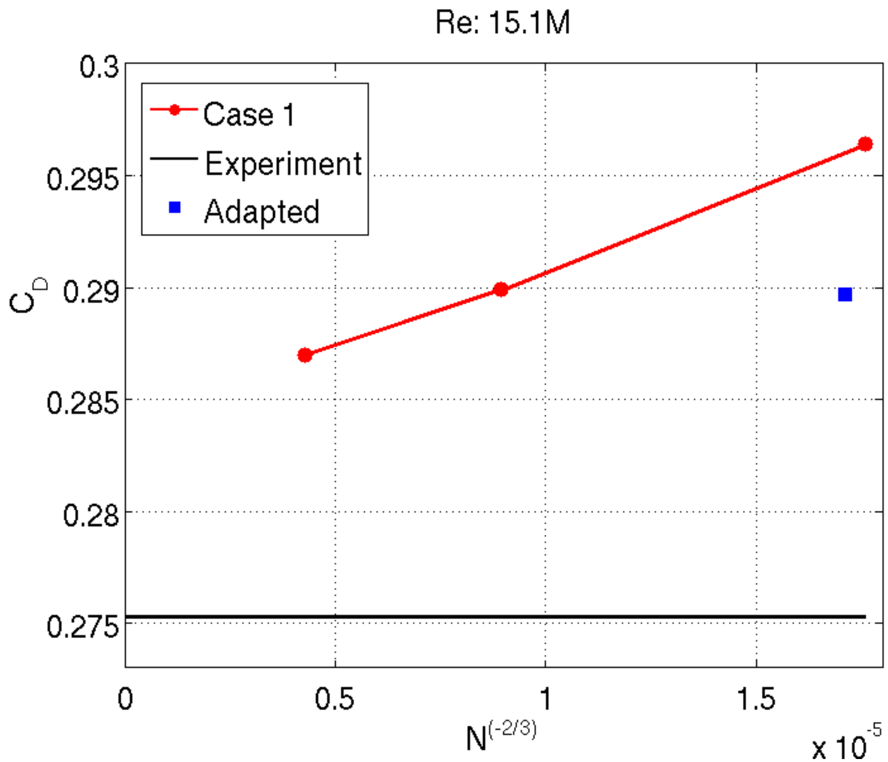




AoA = 7°

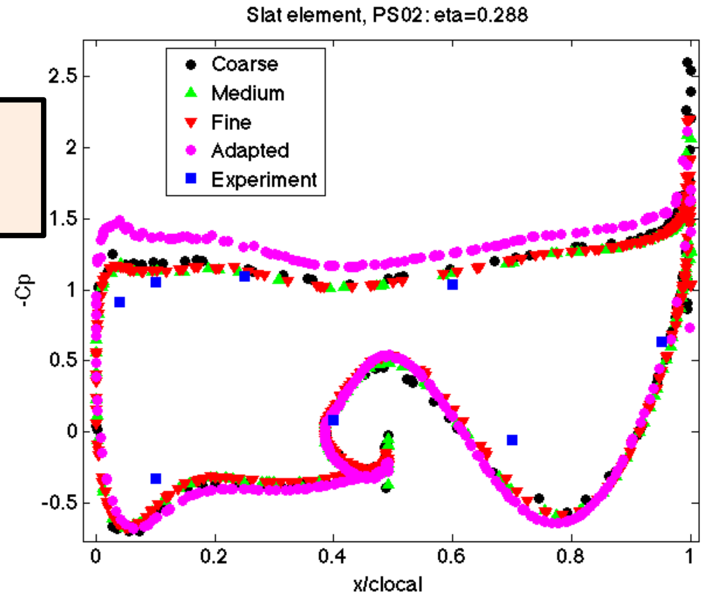
Case 1: Grid Convergence



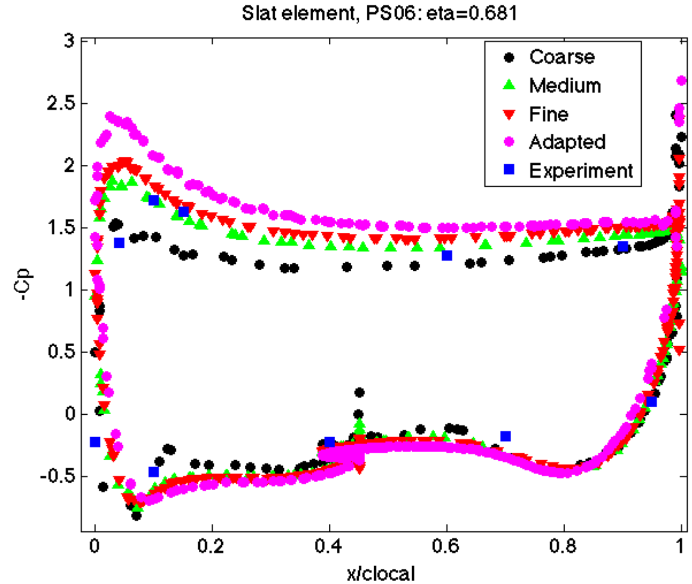


AoA = 16^{o}

Case 1: C_p Plots

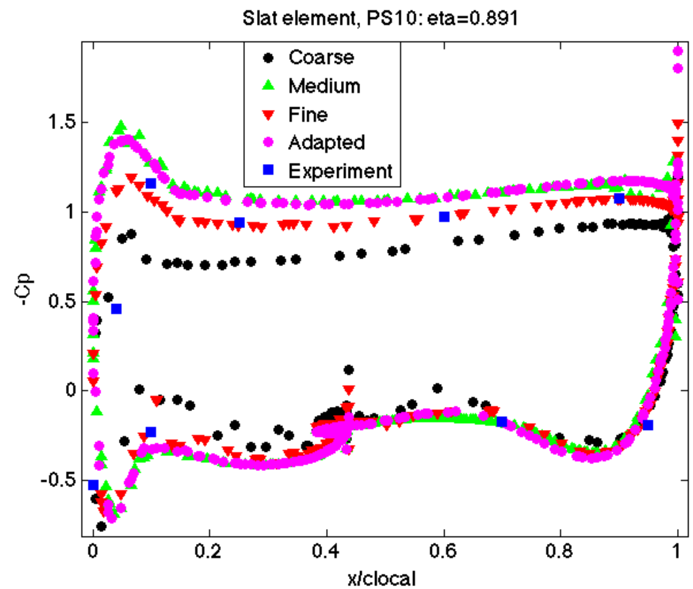


29% span



68% span

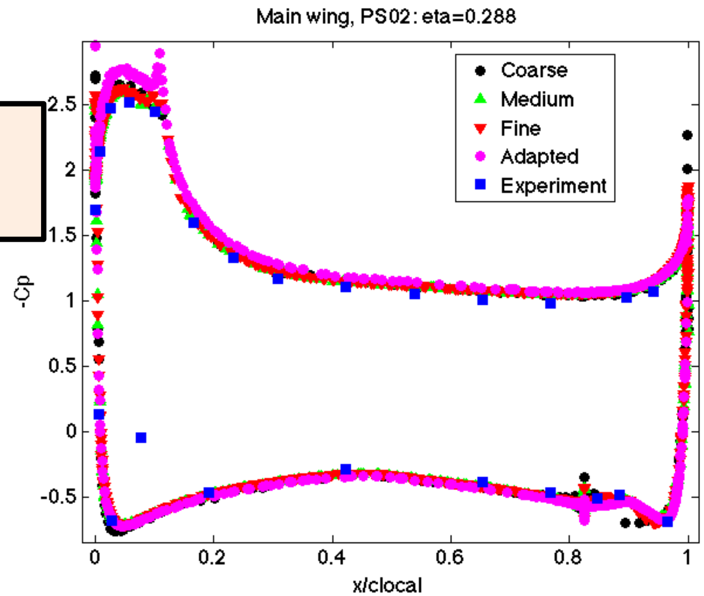
AoA = 7° (Slat element)

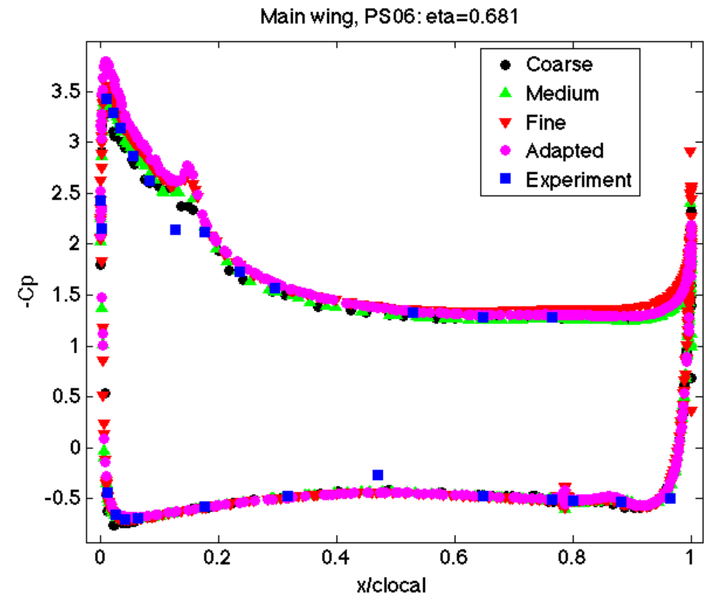


89% span

Case 1: C_p Plots

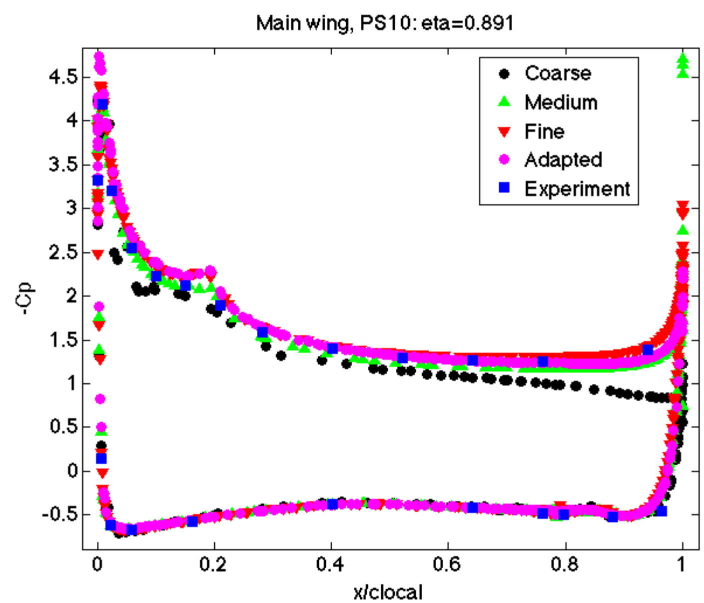
29% span





68% span

AoA = 7º (Main wing)



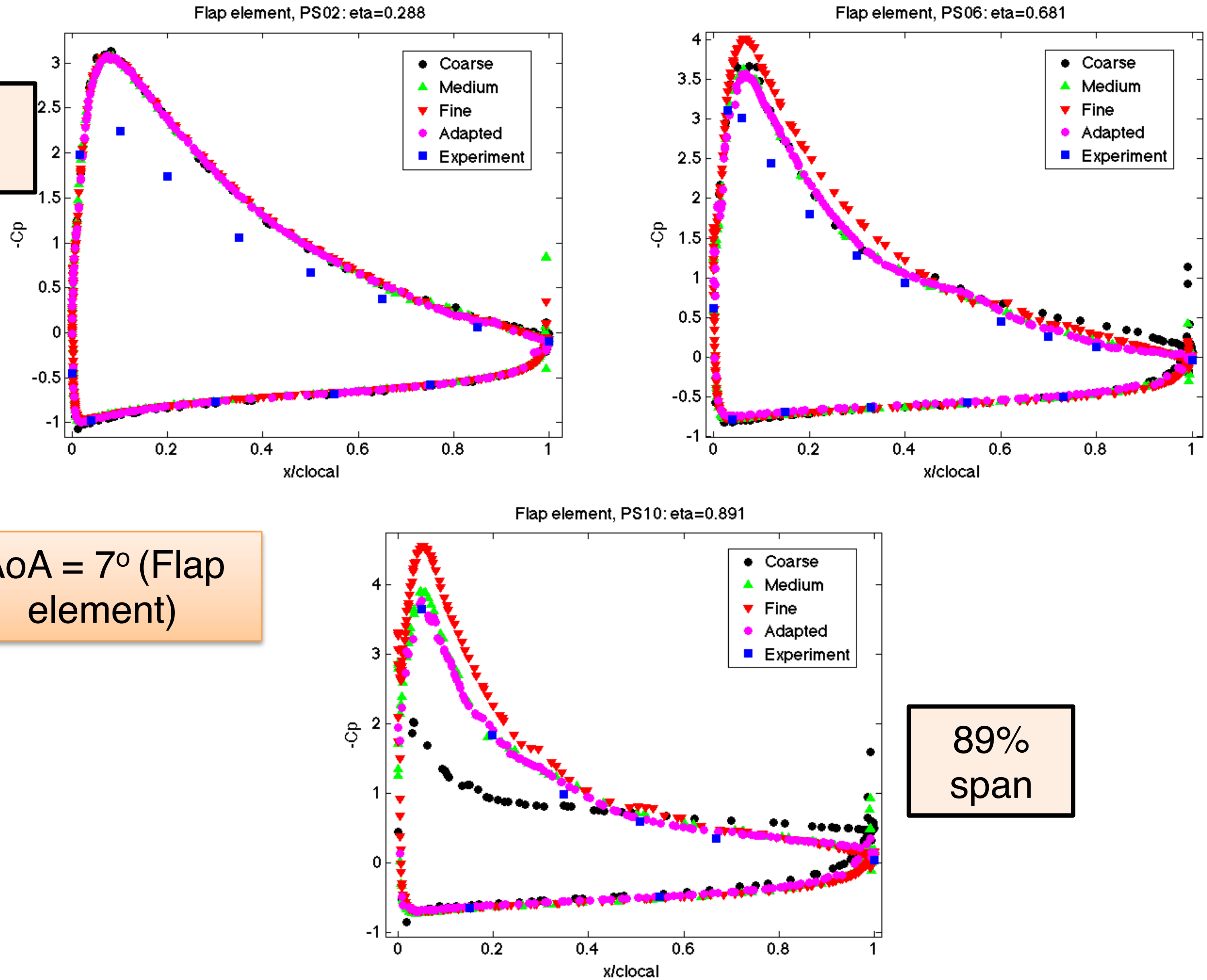
89% span

Case 1: C_p Plots

29% span

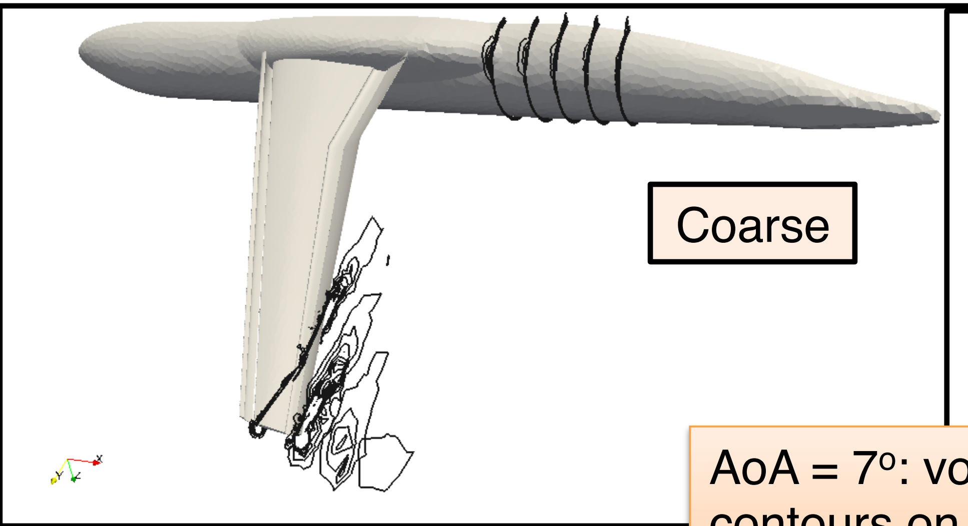
68% span

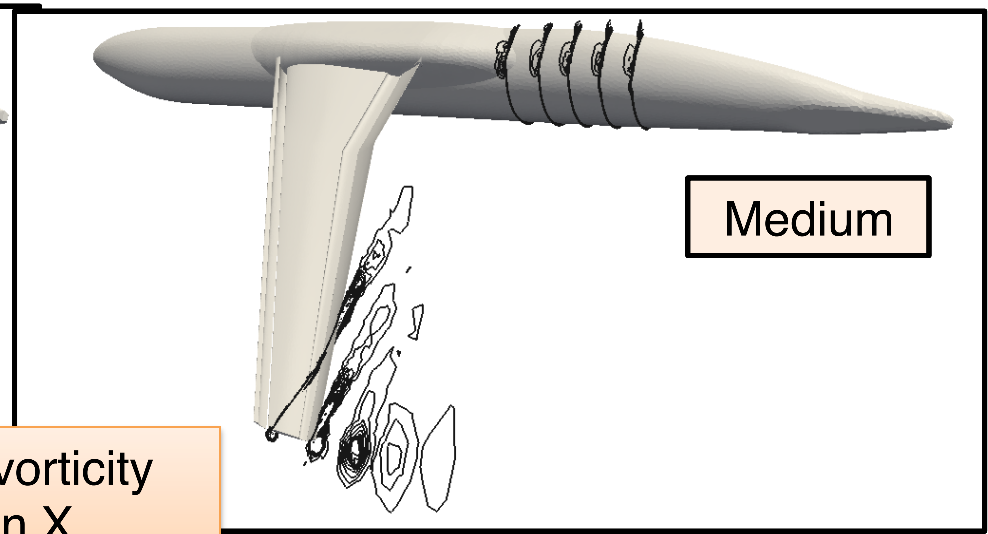
AoA = 7º (Flap element)



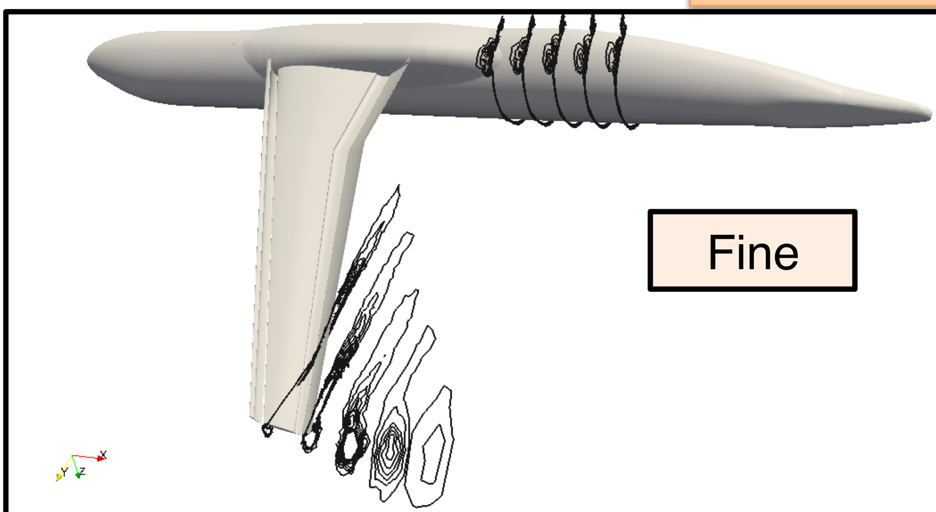
89% span

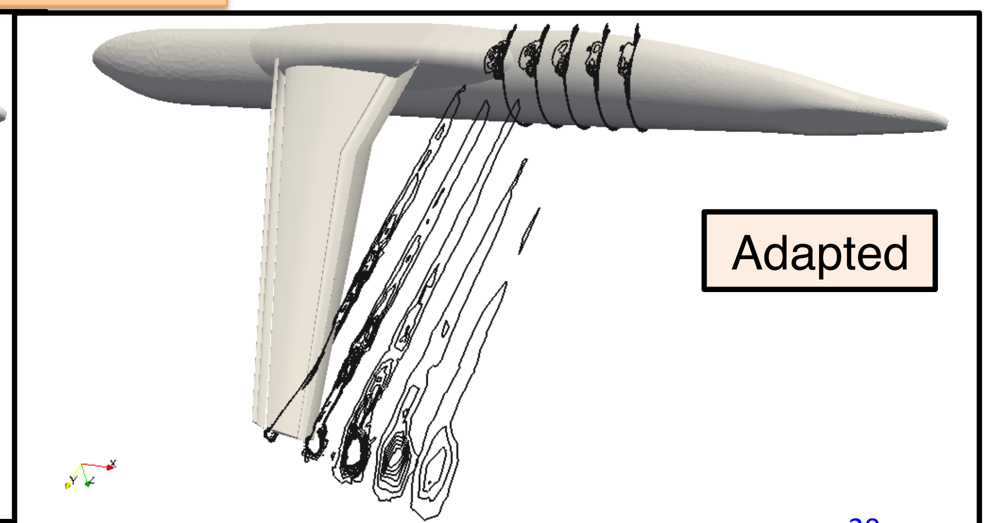
Case 1: Vorticity Contours



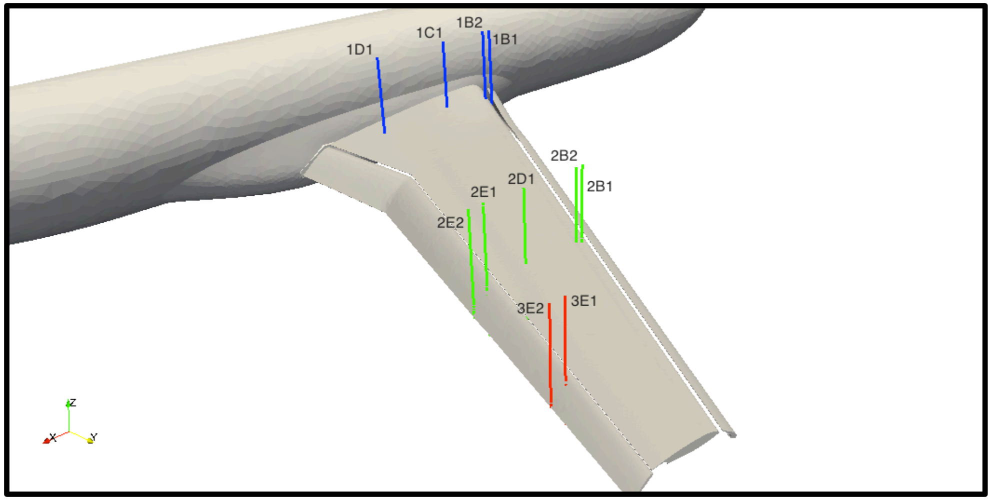


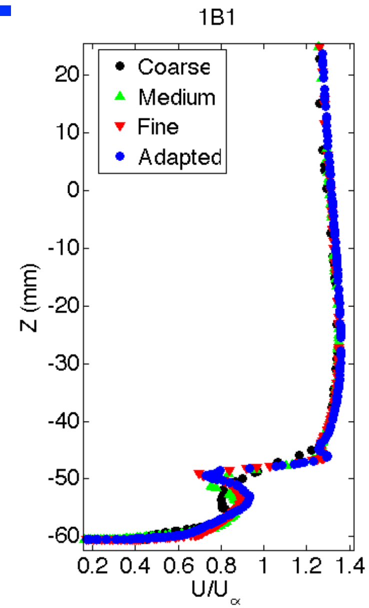
AoA = 7°: vorticity contours on X constant planes

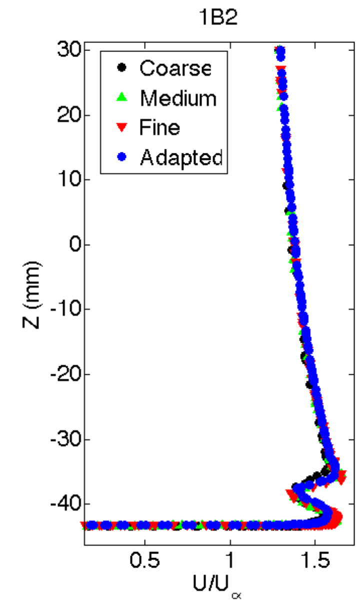


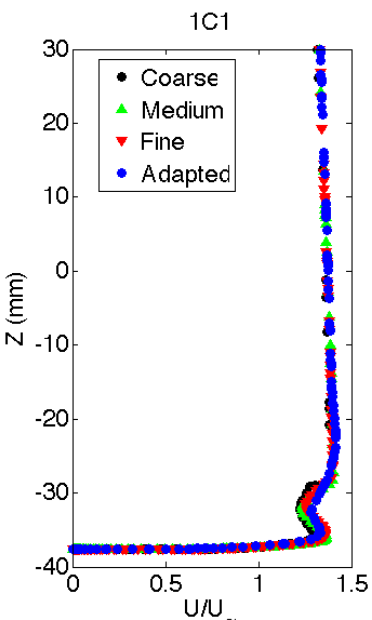


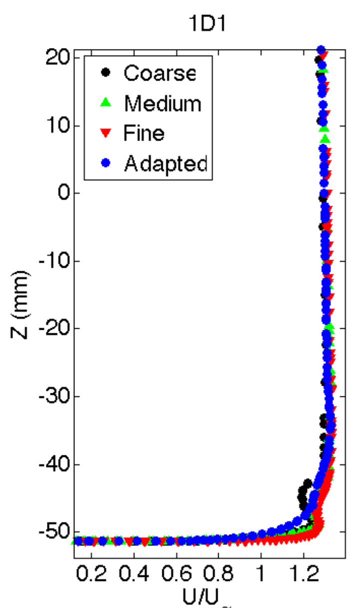
Case 1: Velocity Profiles

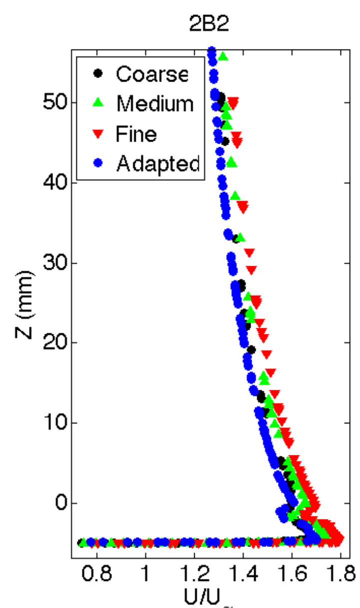


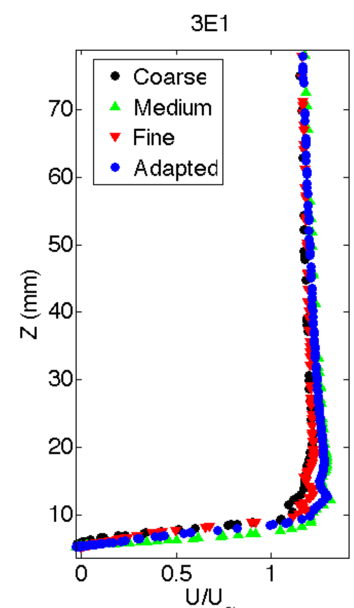


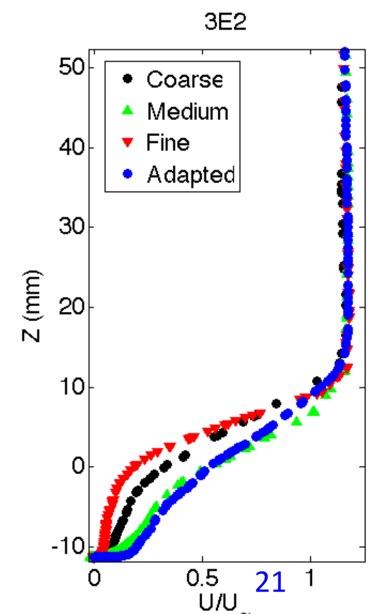




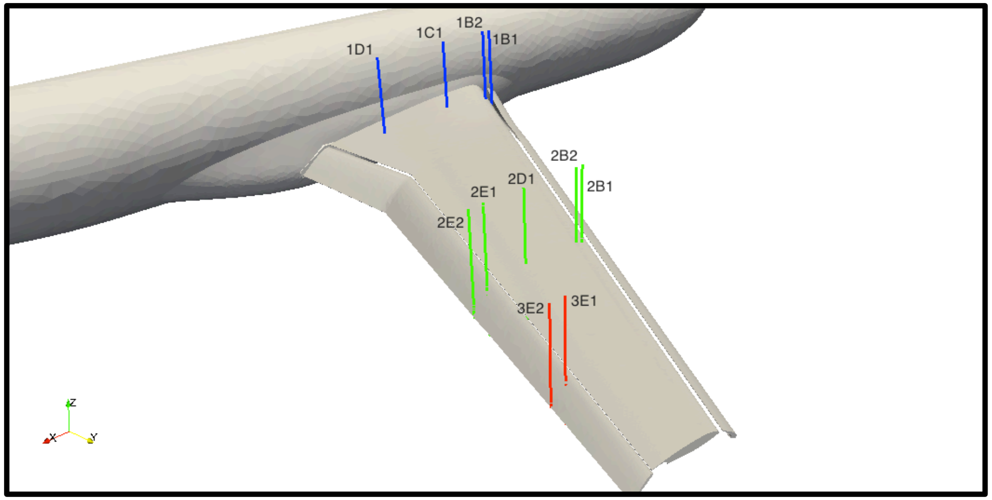




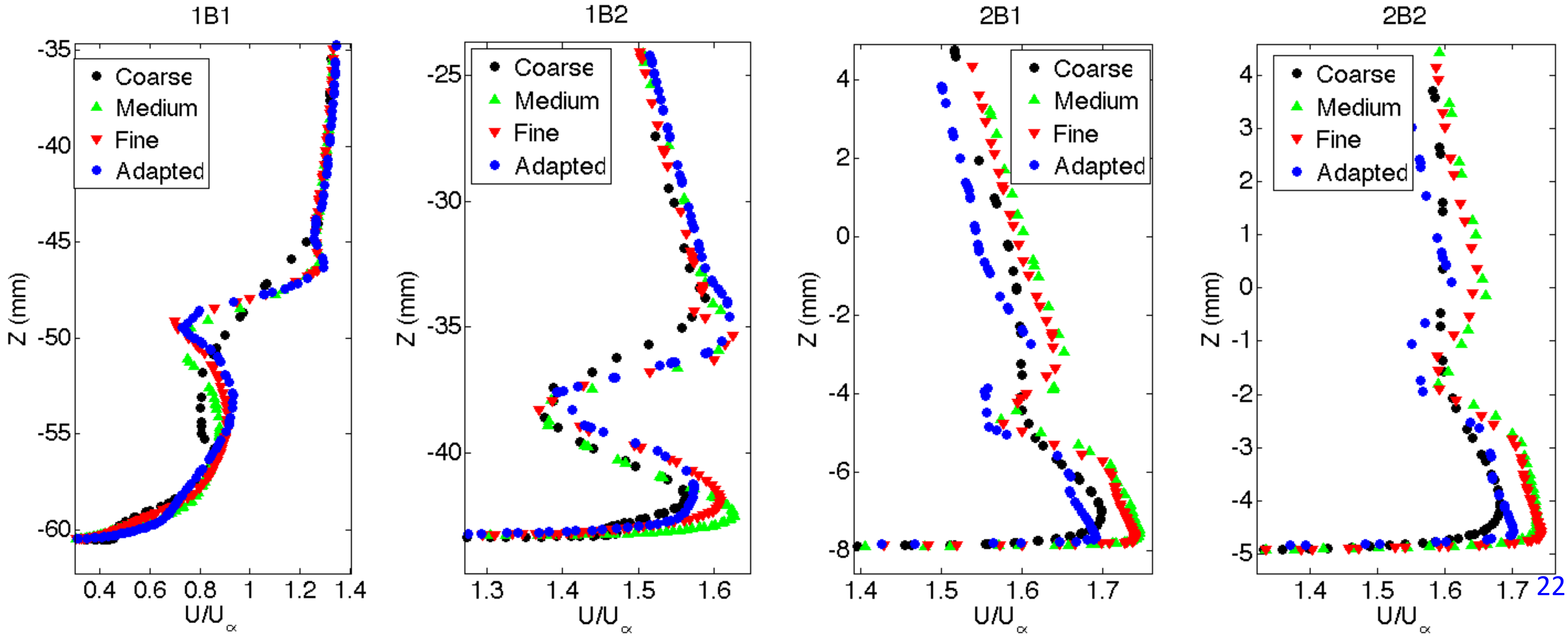




Case 1: Velocity Profiles



Zooms of slat wake profiles



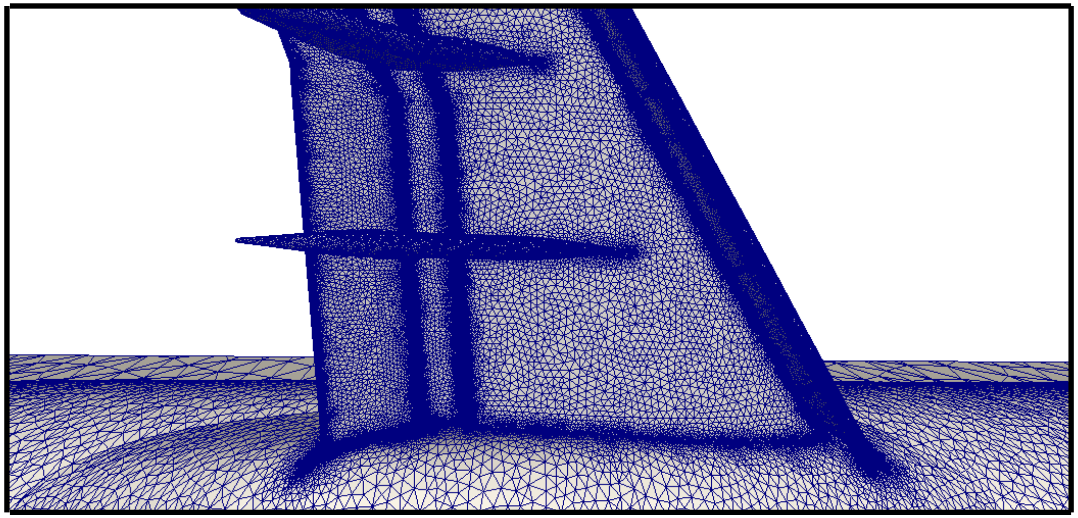
Case 1: Summary

- Reasonable agreement with the experiments
- Adaptivity overall does better near the tip and near the trailing edges in capturing the flow due to higher resolution compared to the coarse mesh, which is of comparable size.
- One adaptive pass is not enough to get accurate grid converged results
- Velocity profile are able to capture wake effects even at medium grid densities
- Flap element shows some difference in C_p values, especially near the root
- Fine mesh overshoots pressure peak on flaps at some locations

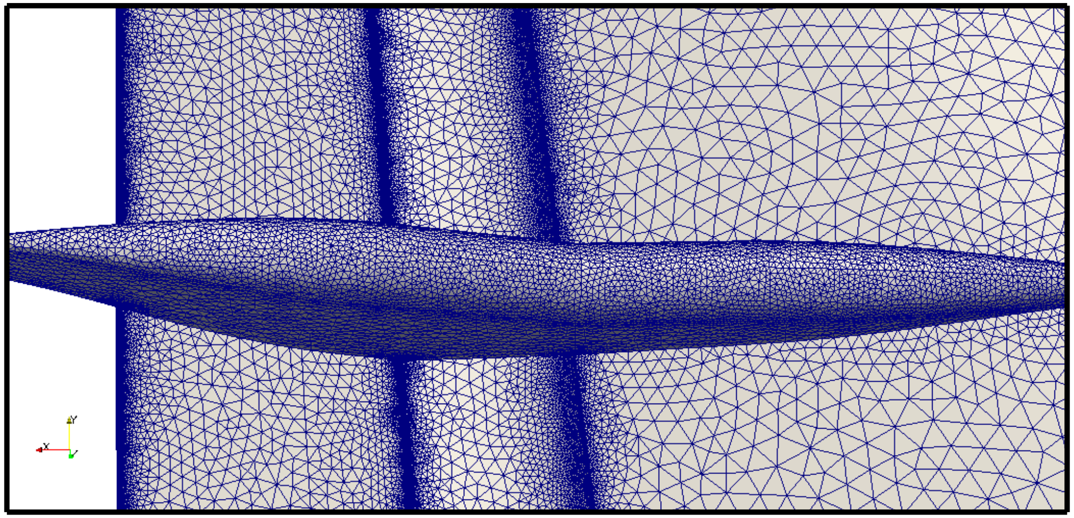
Case 2: Description

- Meshes:
  - Created using gridding guidelines given online
  - Unstructured, with mixed element boundary layers
  - Created in-house using MeshSim software by Simmetrix Inc.
- Mesh statistics:
  - Medium: 98.0M elements, 39.9M nodes
- Cases:
  - Case 2(a): Low Reynolds number = 1.35M
    - Angles of attack: 0, 7, 12, 16, 18.5, 19, 20, 21 (degrees)
  - Case 2(b): High Reynolds number = 15.1M
    - Angles of attack: 0, 7, 12, 16, 18.5, 20, 21, 22.4 (degrees)
- Solved on Mira BG/Q on 32k processors

Case 2: Mesh

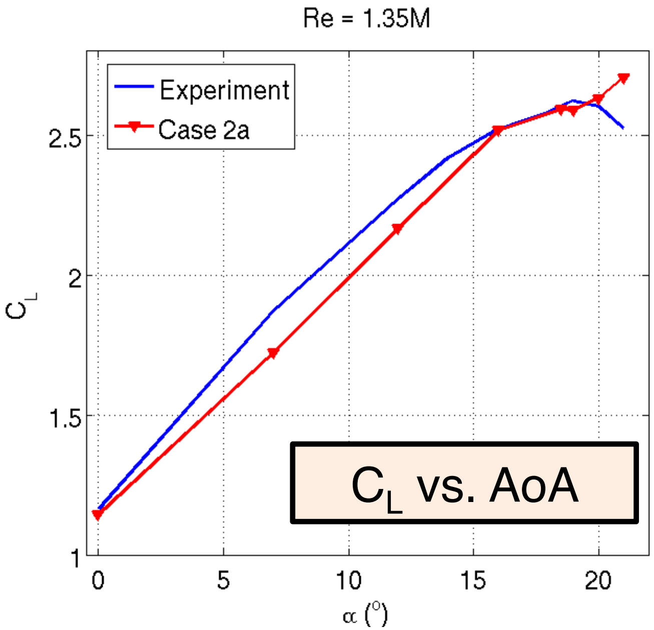


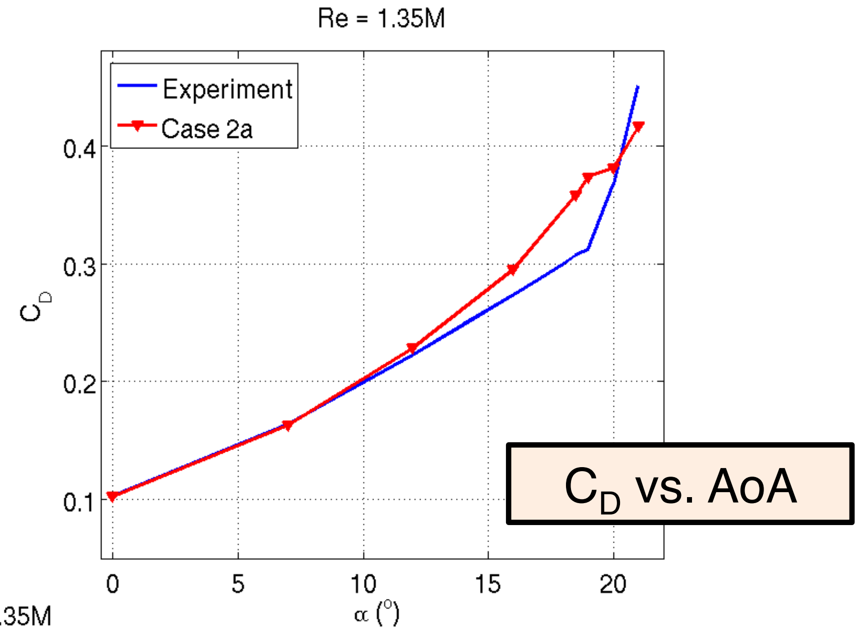
Mesh created with same attributes as for medium mesh in Case 1

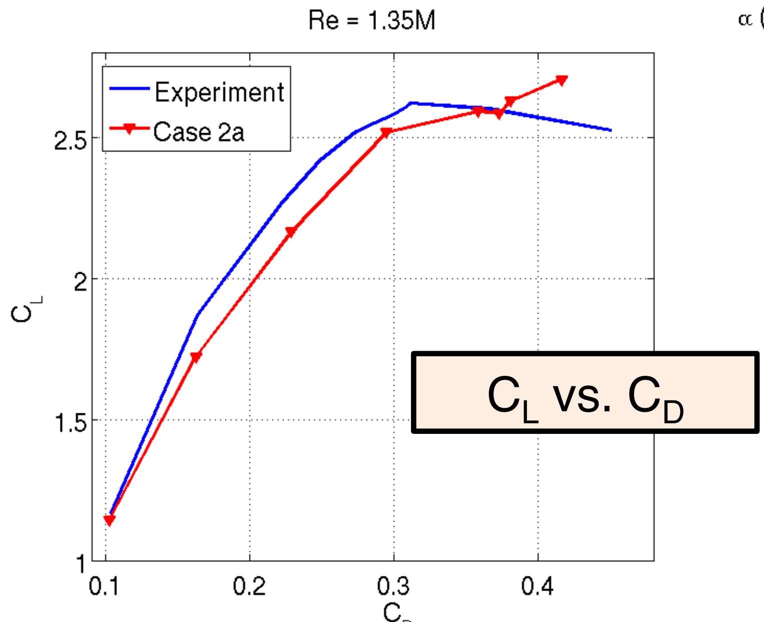


Zoom of the flap fairing

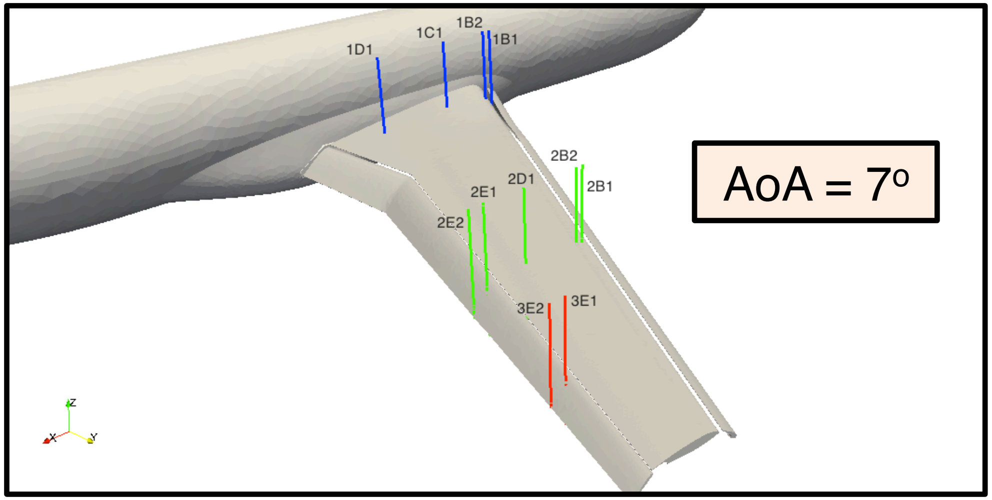
Case 2a: Lift and Drag

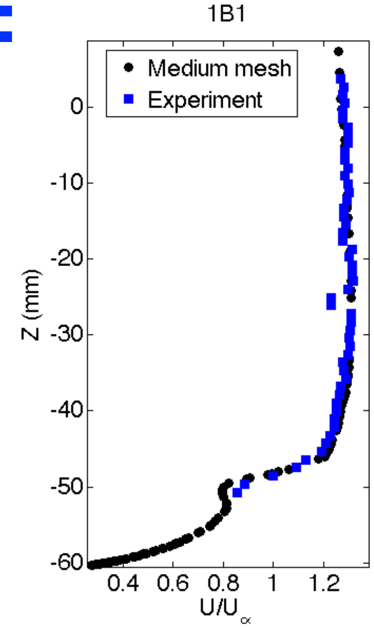


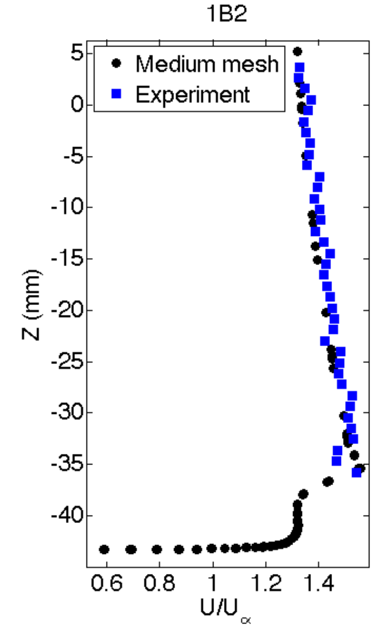


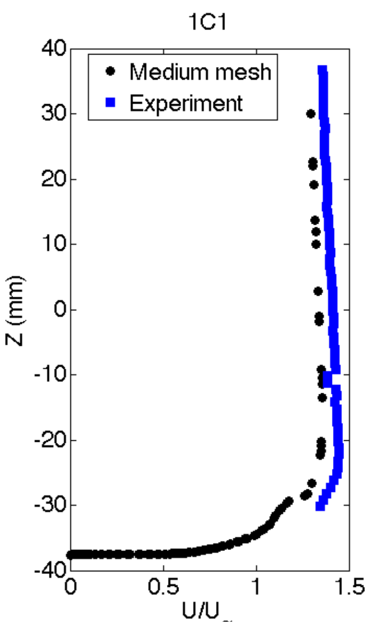


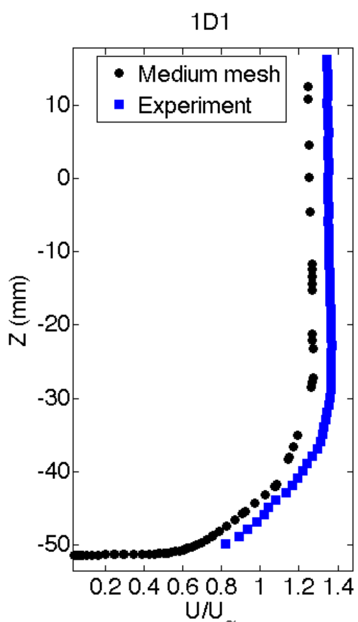
Case 2a: Velocity Profiles

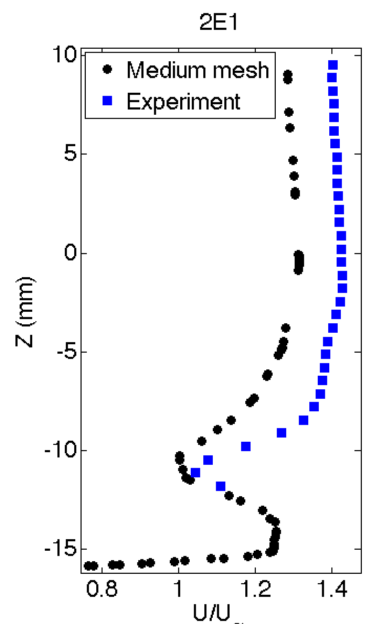


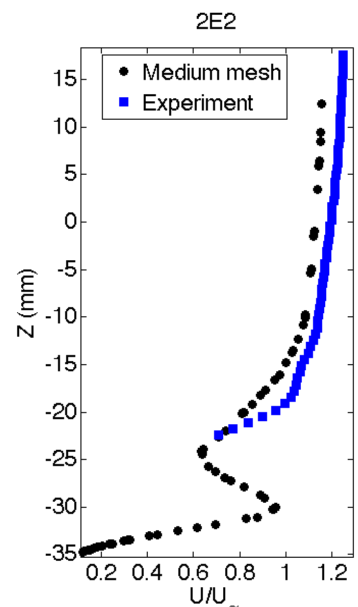


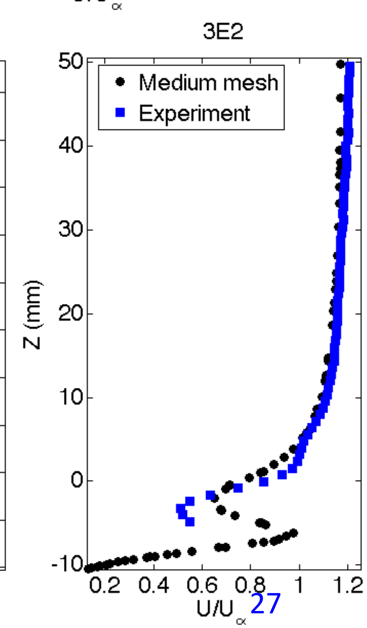




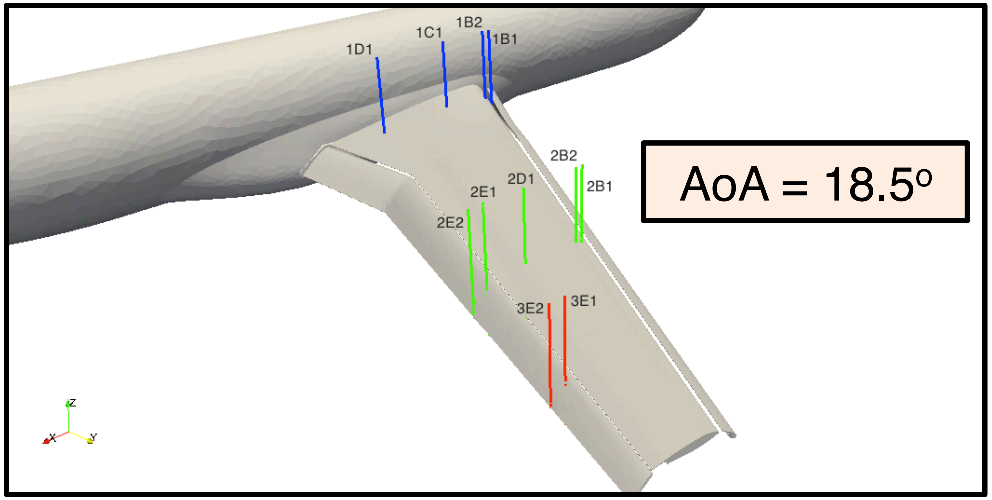


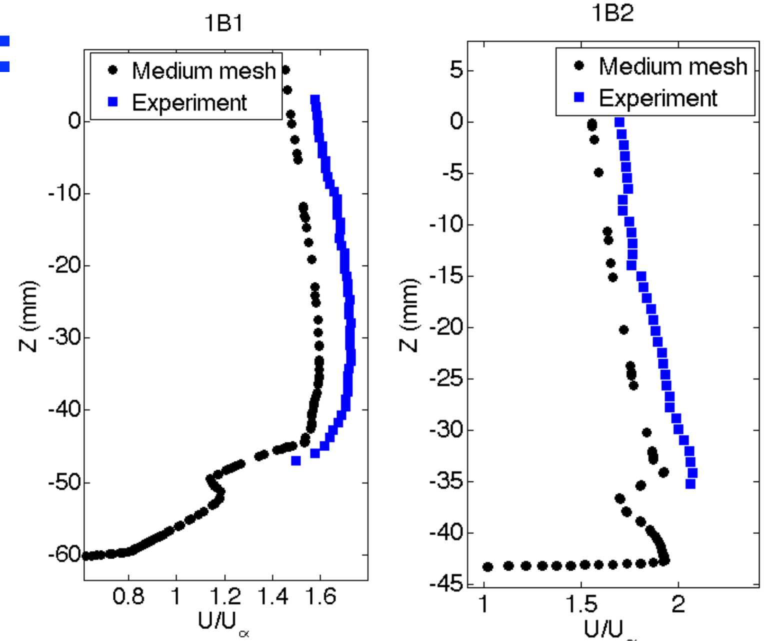


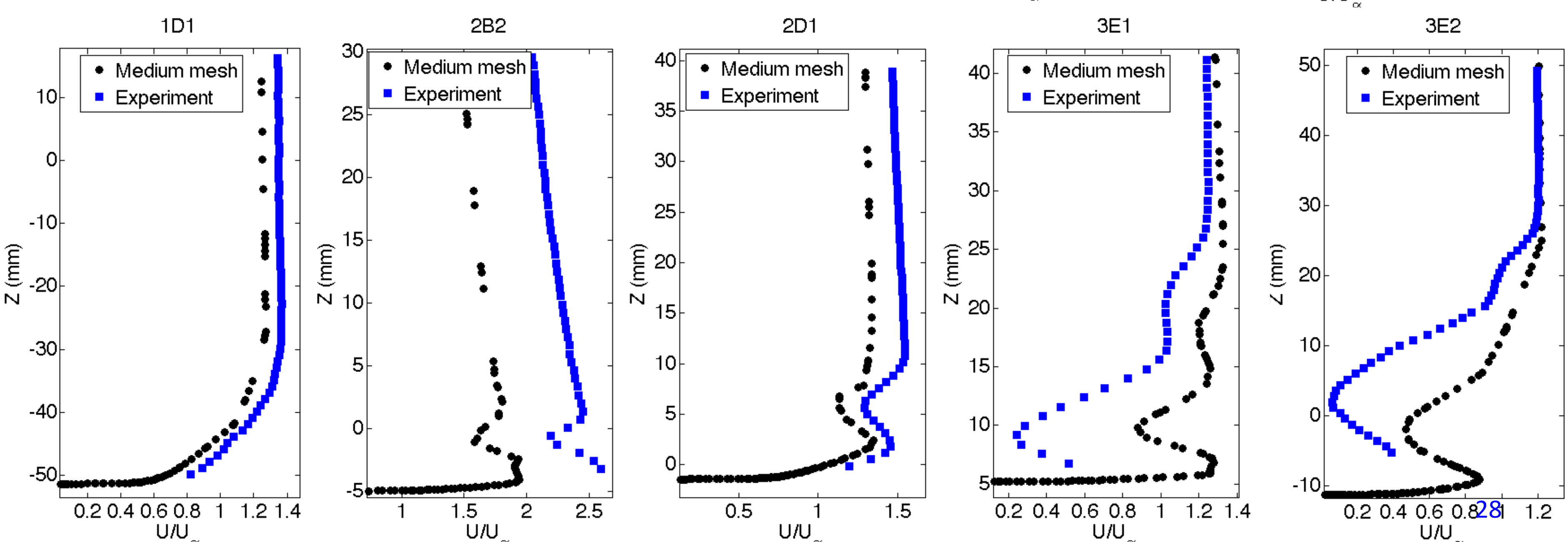




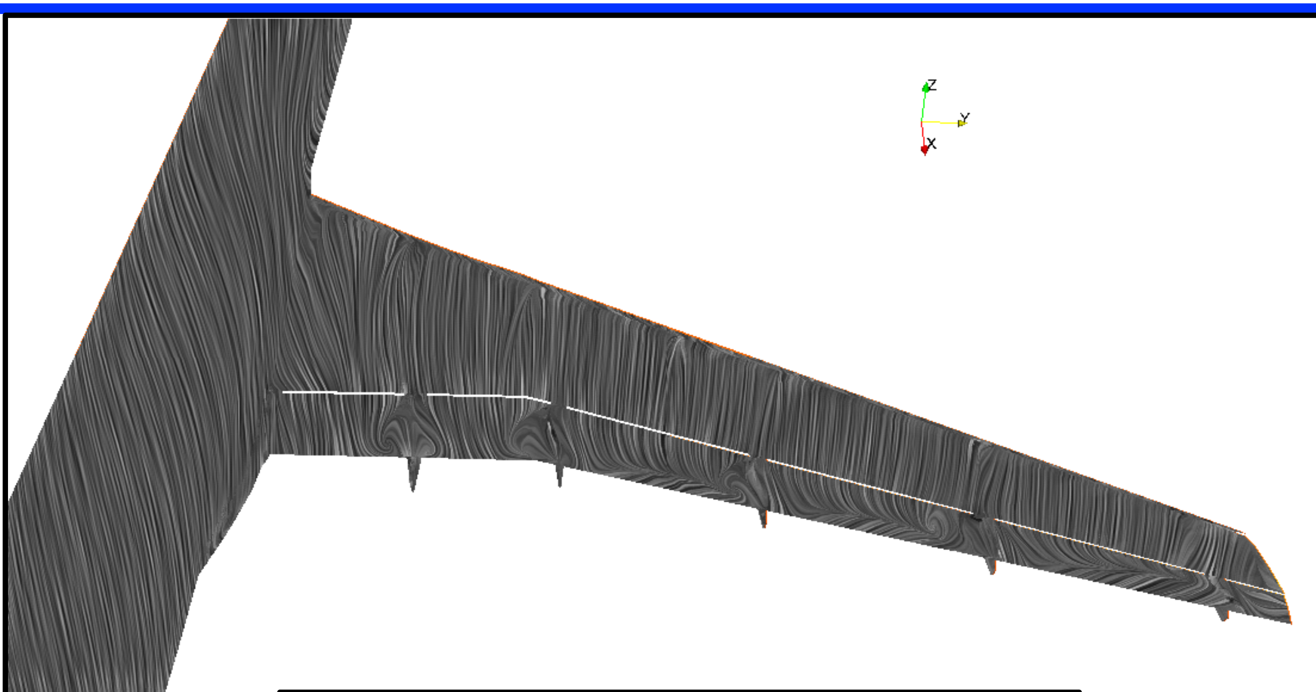
Case 2a: Velocity Profiles



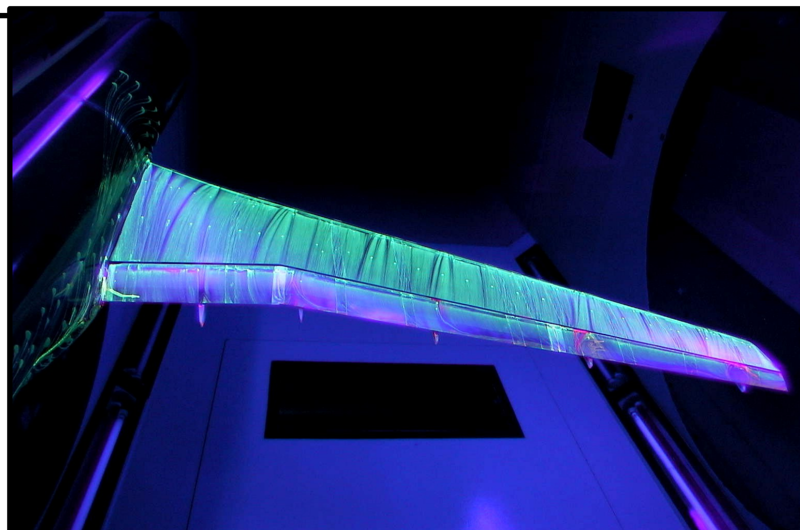




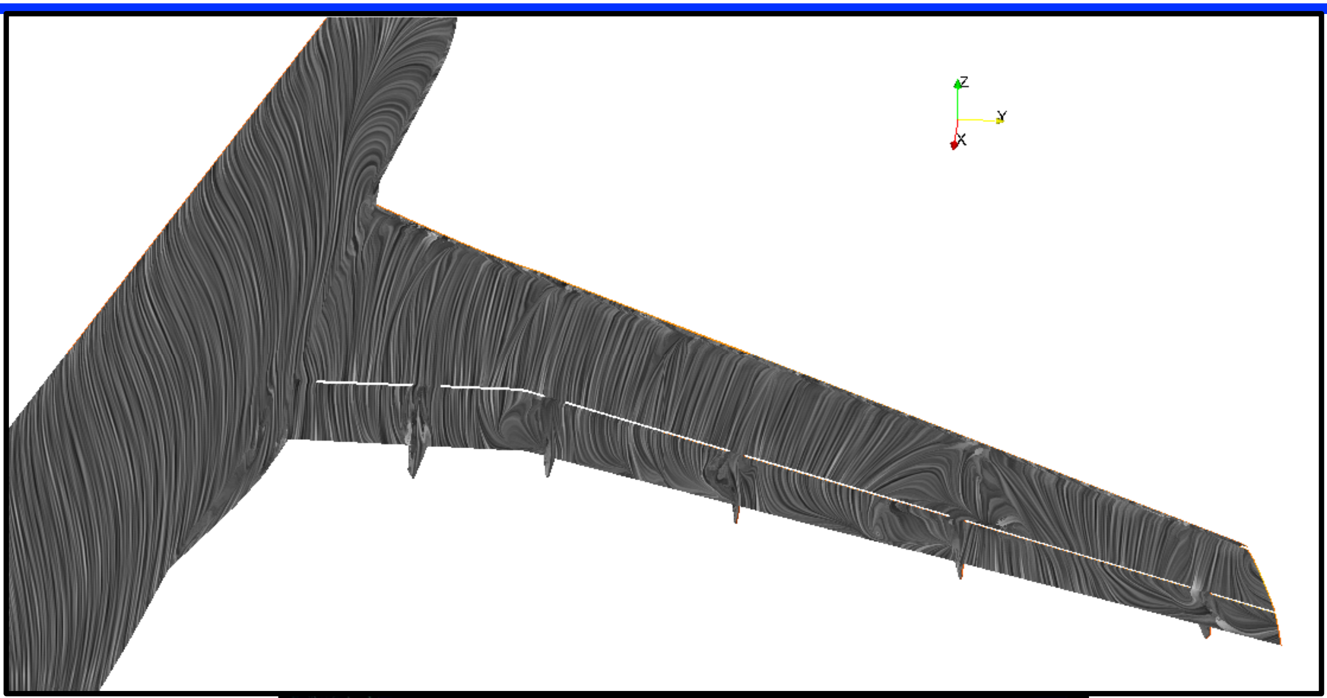
Case 2a: Oil Flow



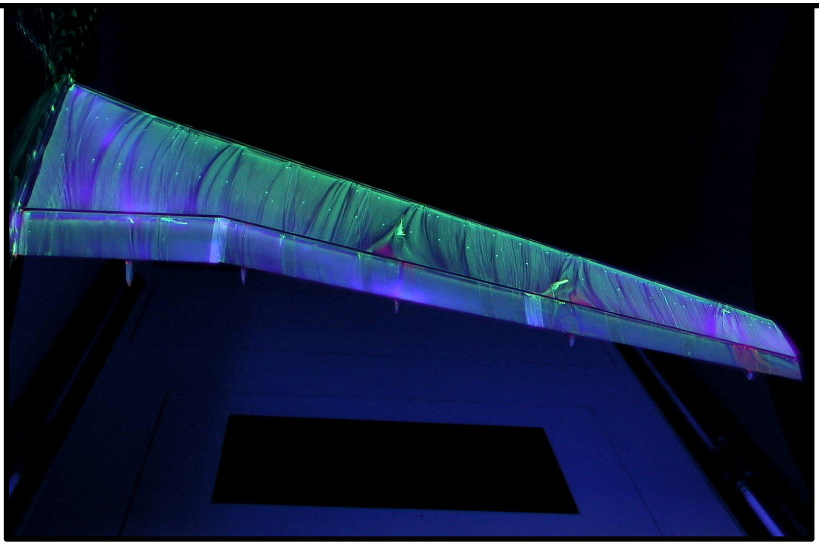
AoA = 7°



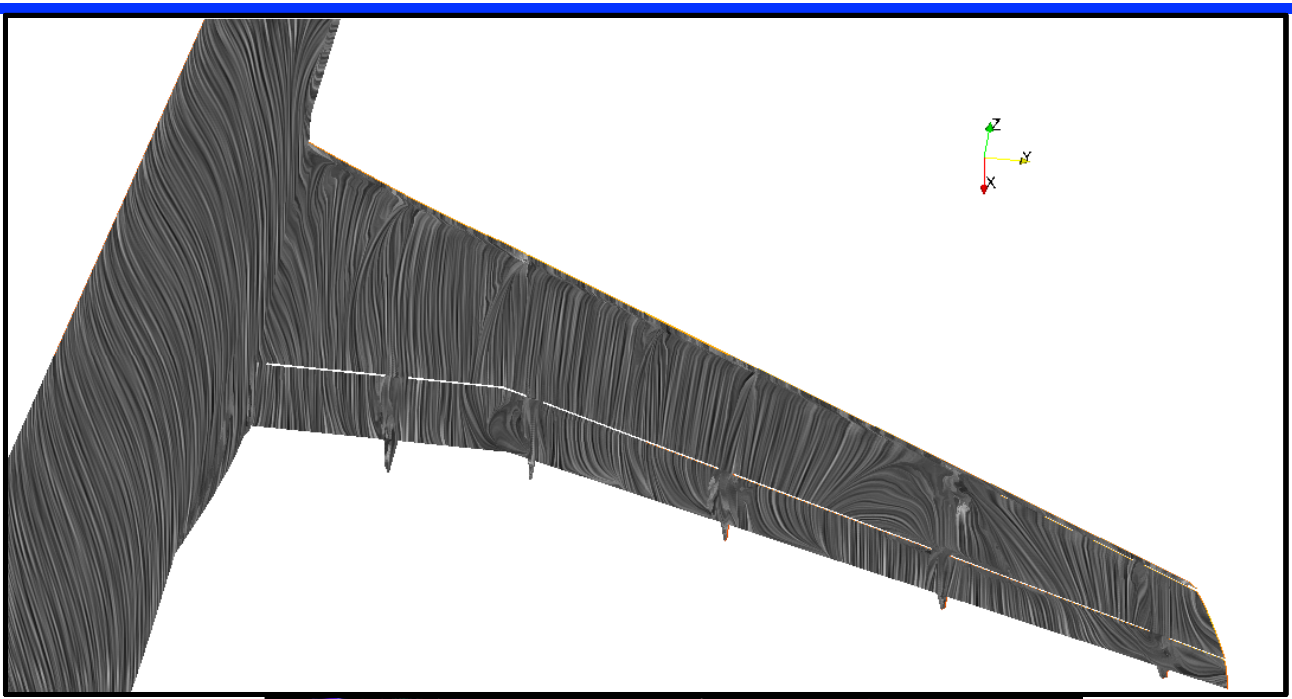
Case 2a: Oil Flow



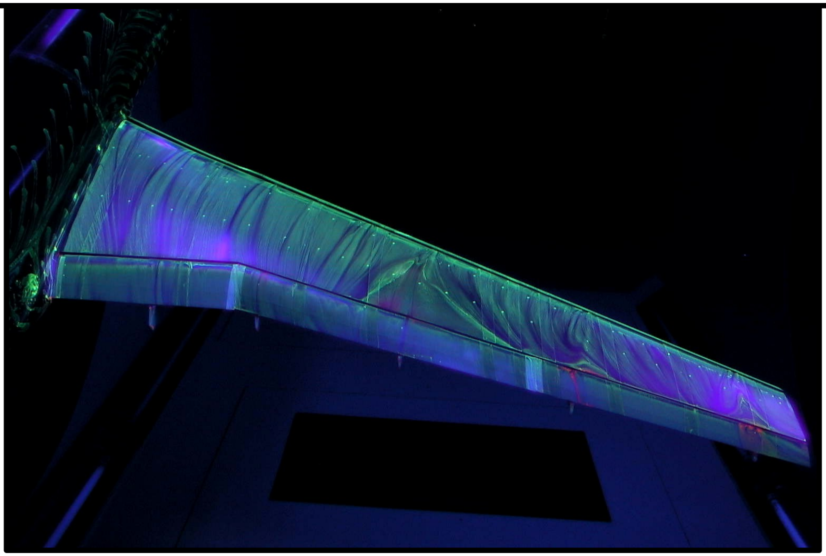
AoA = 18.5^{o}



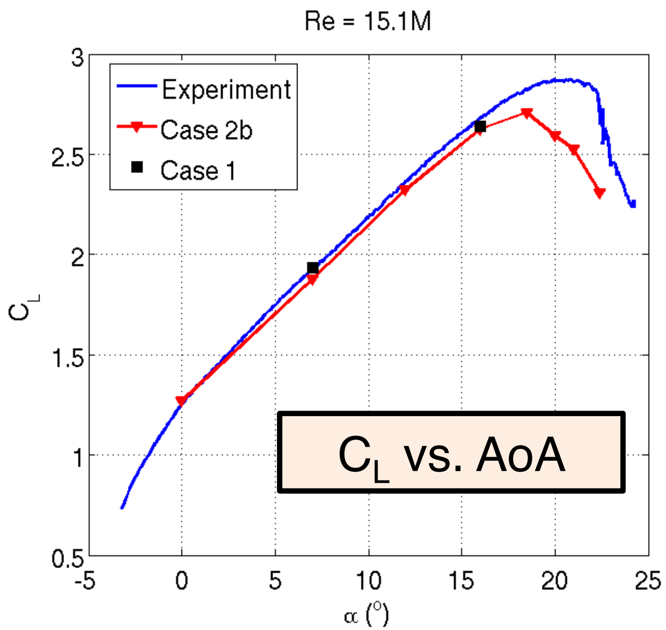
Case 2a: Oil Flow

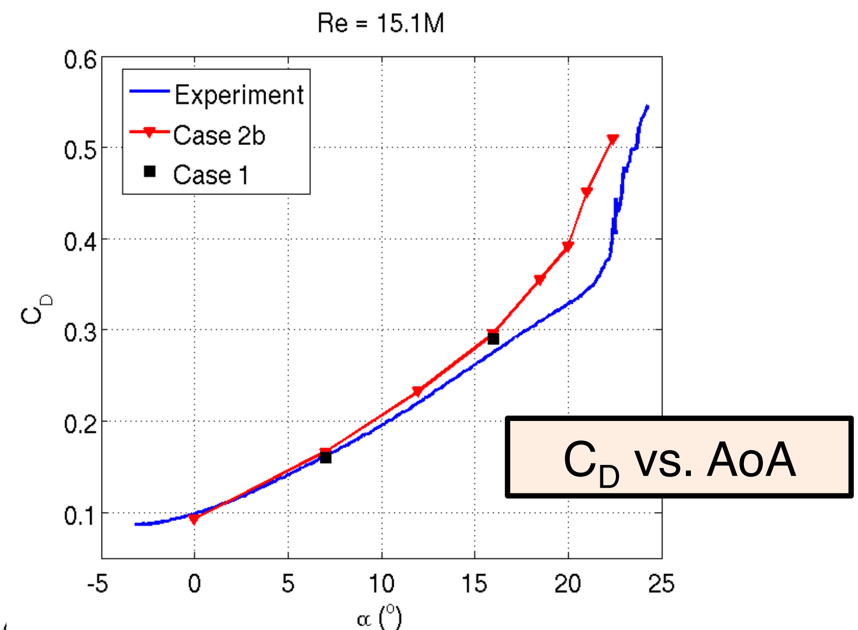


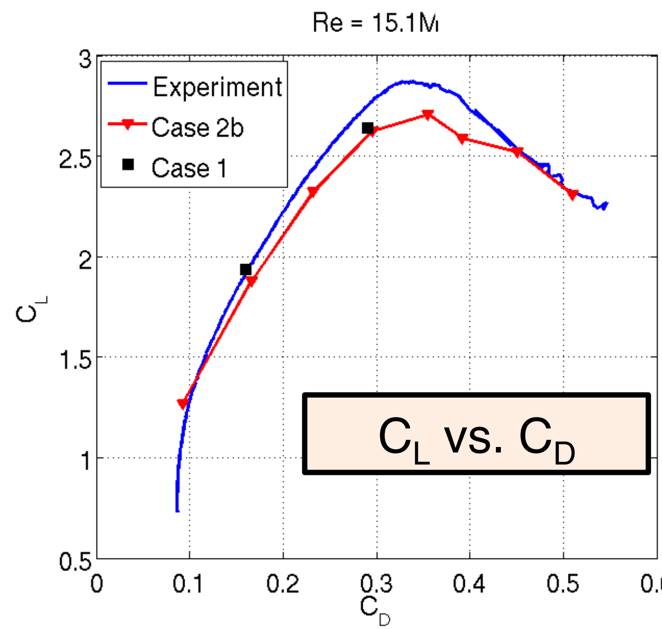
AoA = 21°



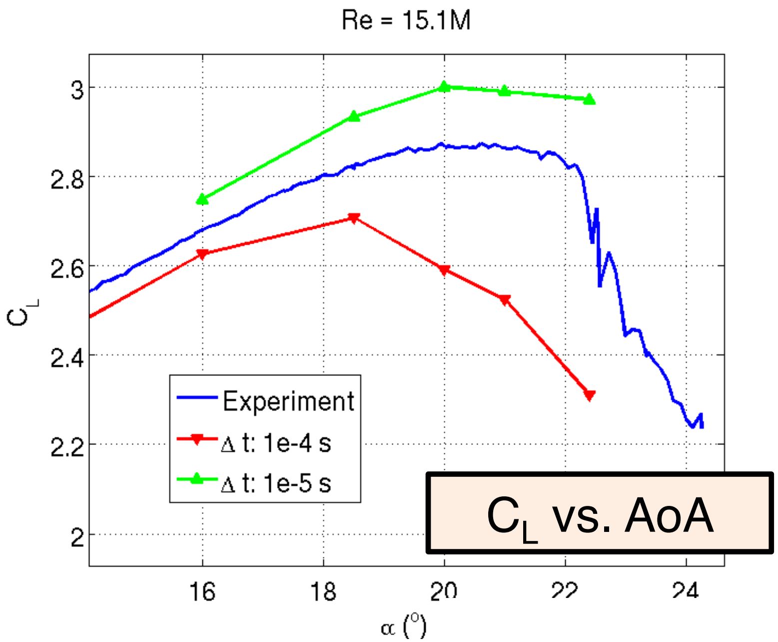
Case 2b: Lift and Drag

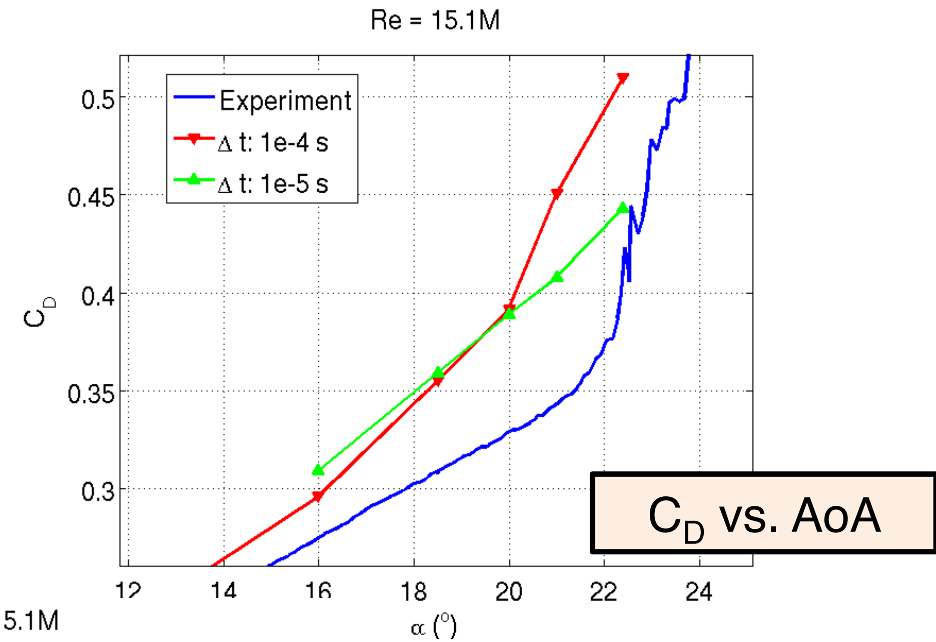




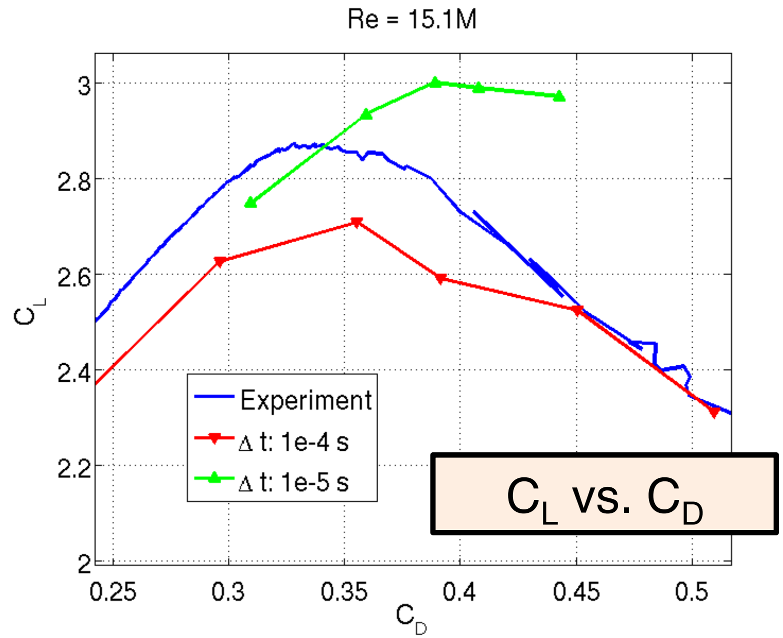


Case 2b: Lift and Drag





Time step dependence at high AoA



Case 2b: Effect of brackets

AoA = 7°

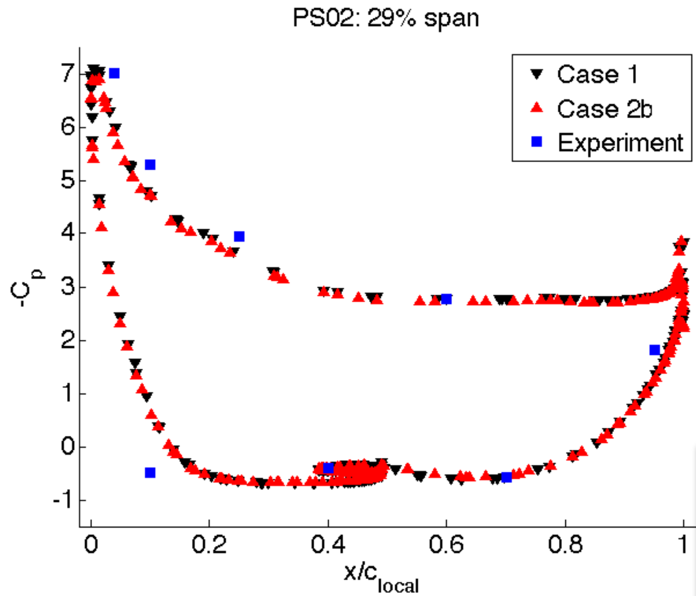
Case	C_L	C_D
Case 1	1.923	0.160
Case 2b	1.876	0.166
Experiments	1.930	0.162

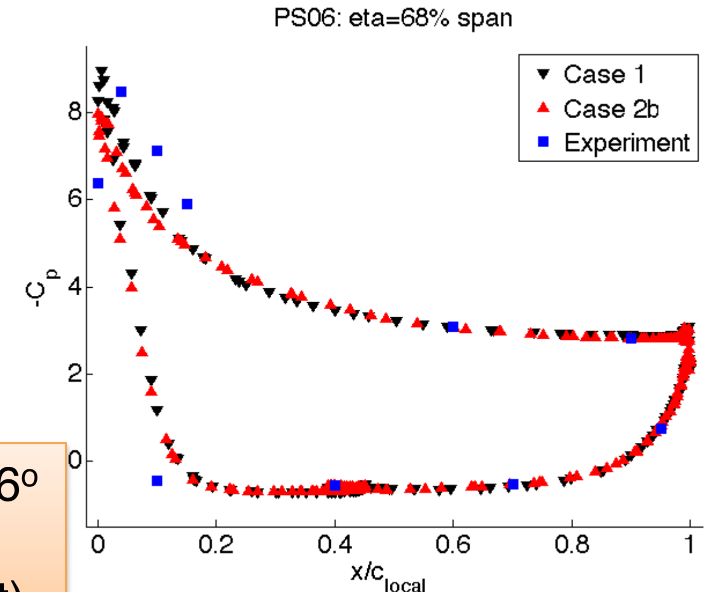
Effect: Lower C_L, higher C_D

AoA = 16°

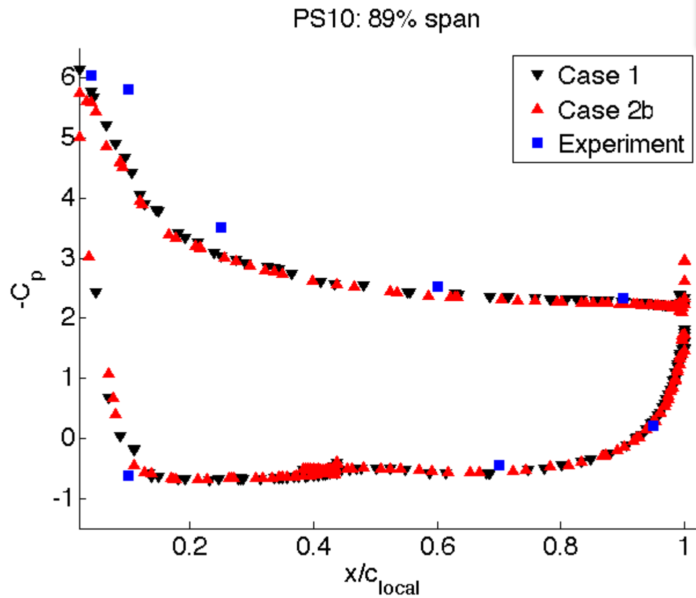
Case	C_L	C_D
Case 1	2.629	0.289
Case 2b	2.625	0.296
Experiments	2.679	0.275

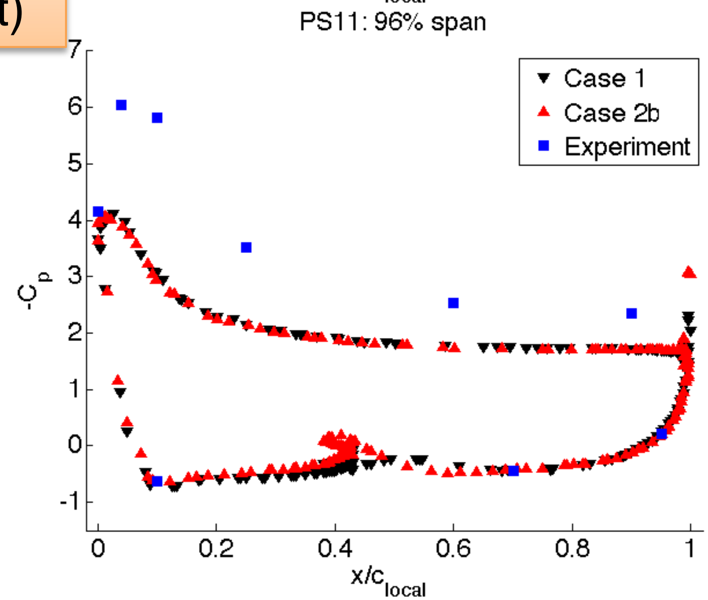
Case 2b: Effect of brackets



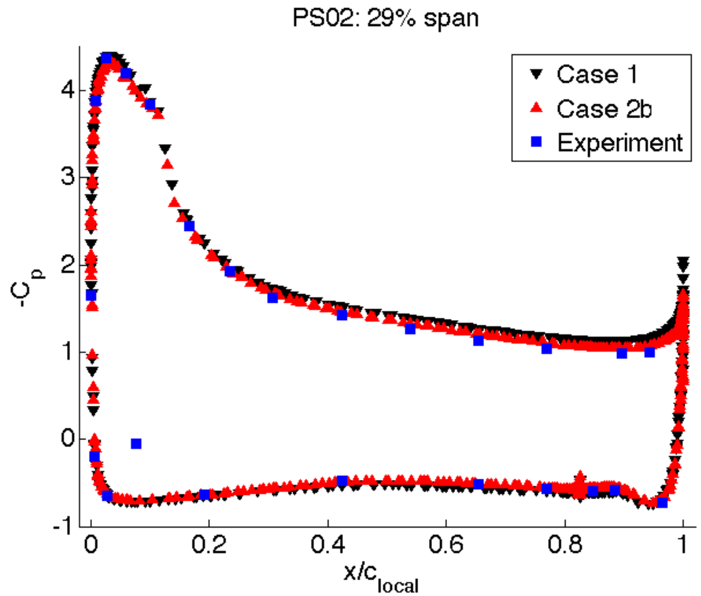


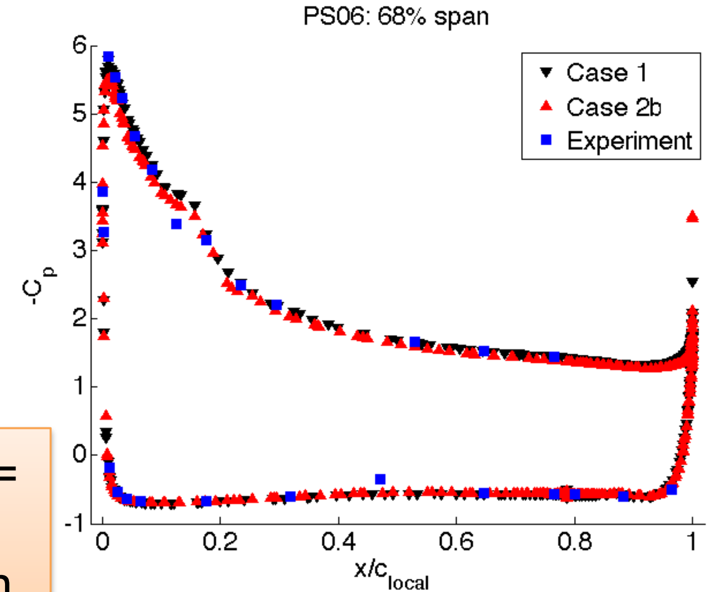
AoA = 16^o (Slat element)



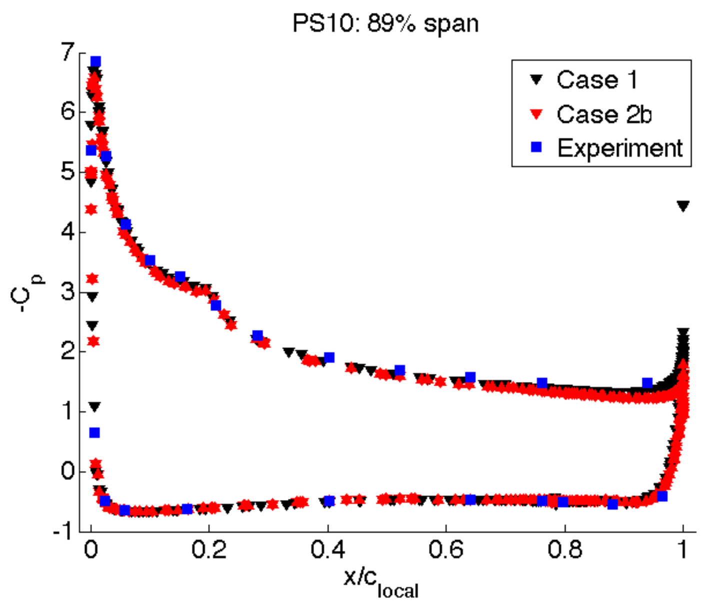


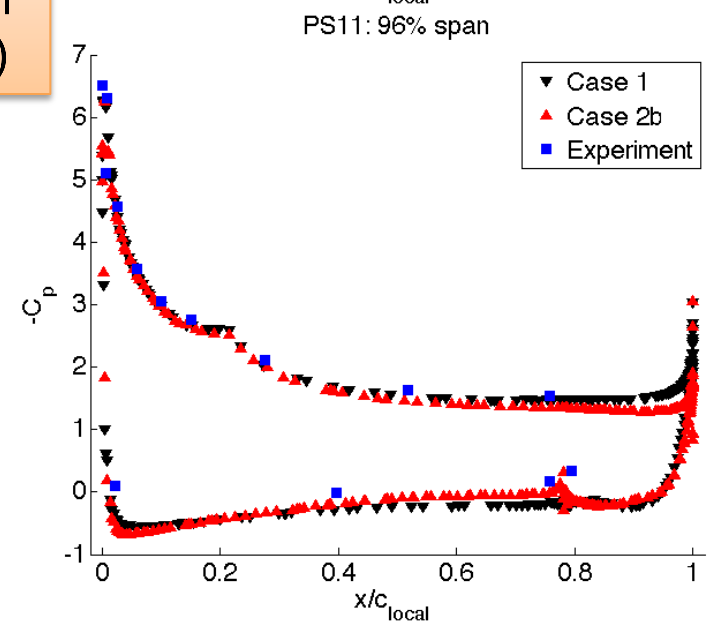
Case 2b: Effect of brackets



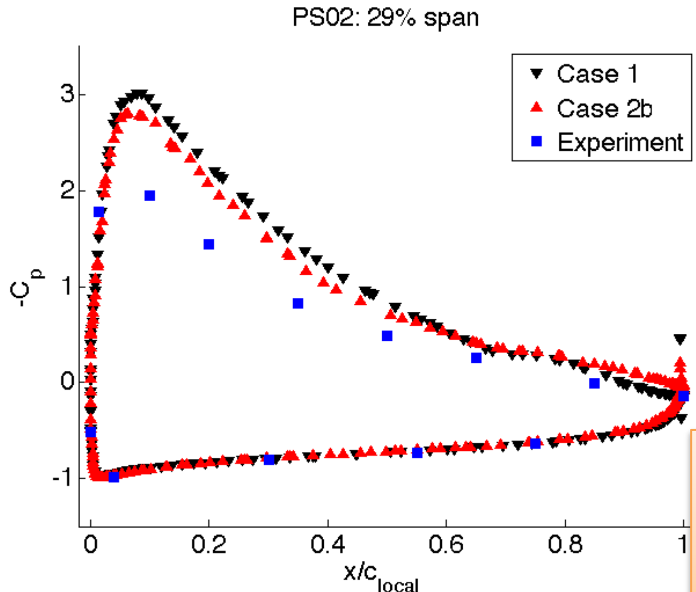


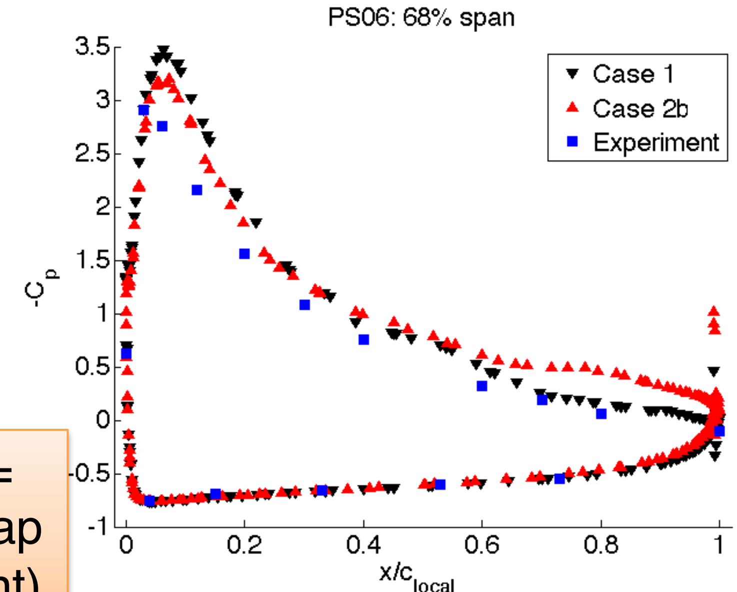
AoA = 16^{o} (Main wing)



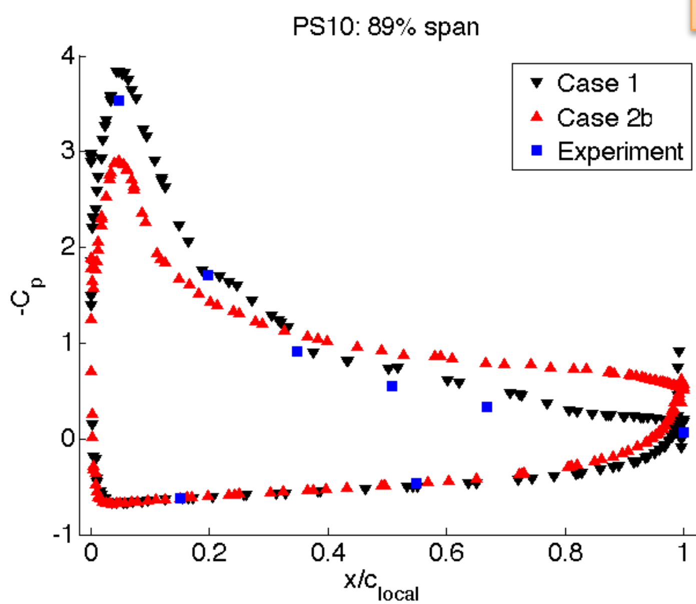


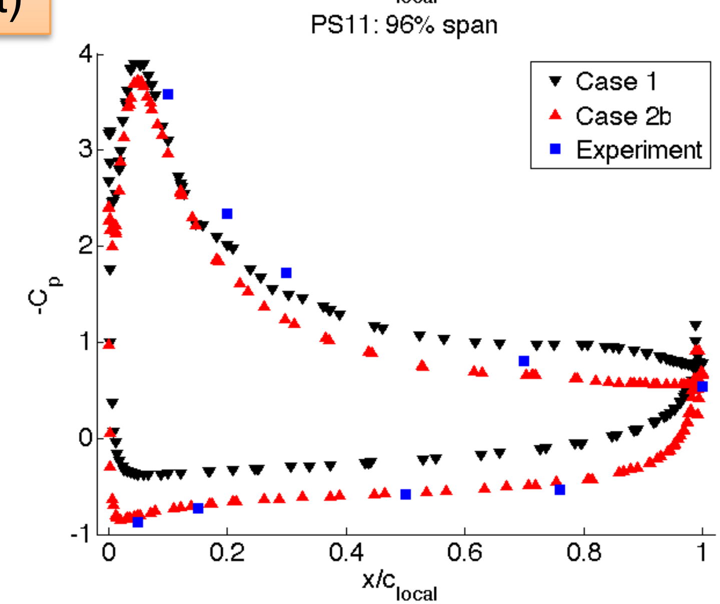
Case 2b: Effect of brackets



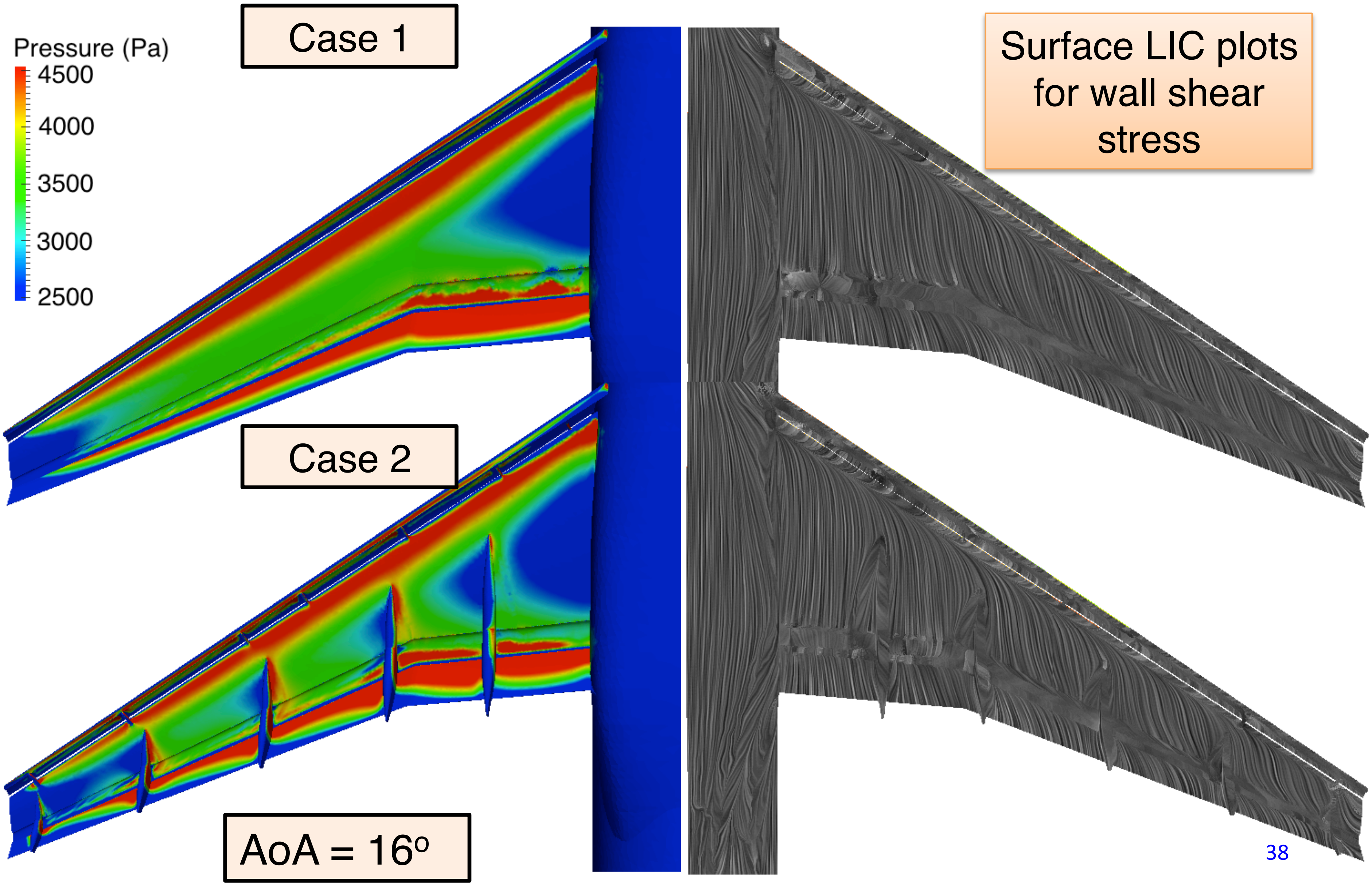


AoA = 16° (Flap element)





Case 2a: Pressure and LIC



Case 2: Summary

- Overall reasonable agreement with the experimental data
- Higher angles of attack show sensitiveness to the time step size (unsteady behavior might need better turbulence modeling)
- Good velocity profiles with capturing of wakes!
- Drag is over predicted at higher angles of attack.
- Effects of brackets:
  – Lower lift, higher drag
  – Slight effect on $C_{p,}$ pressure peaks under predicted

Future Work

- More adaptive passes to reach adaptive grid independent solutions (need parallel adaptivity)

- Adaptive DES simulations of Case 2a at 7^o, 18.5^o, 21^o AoA on massively parallel systems to capture unsteadiness

- Taking part in future prediction workshops

THANK YOU!